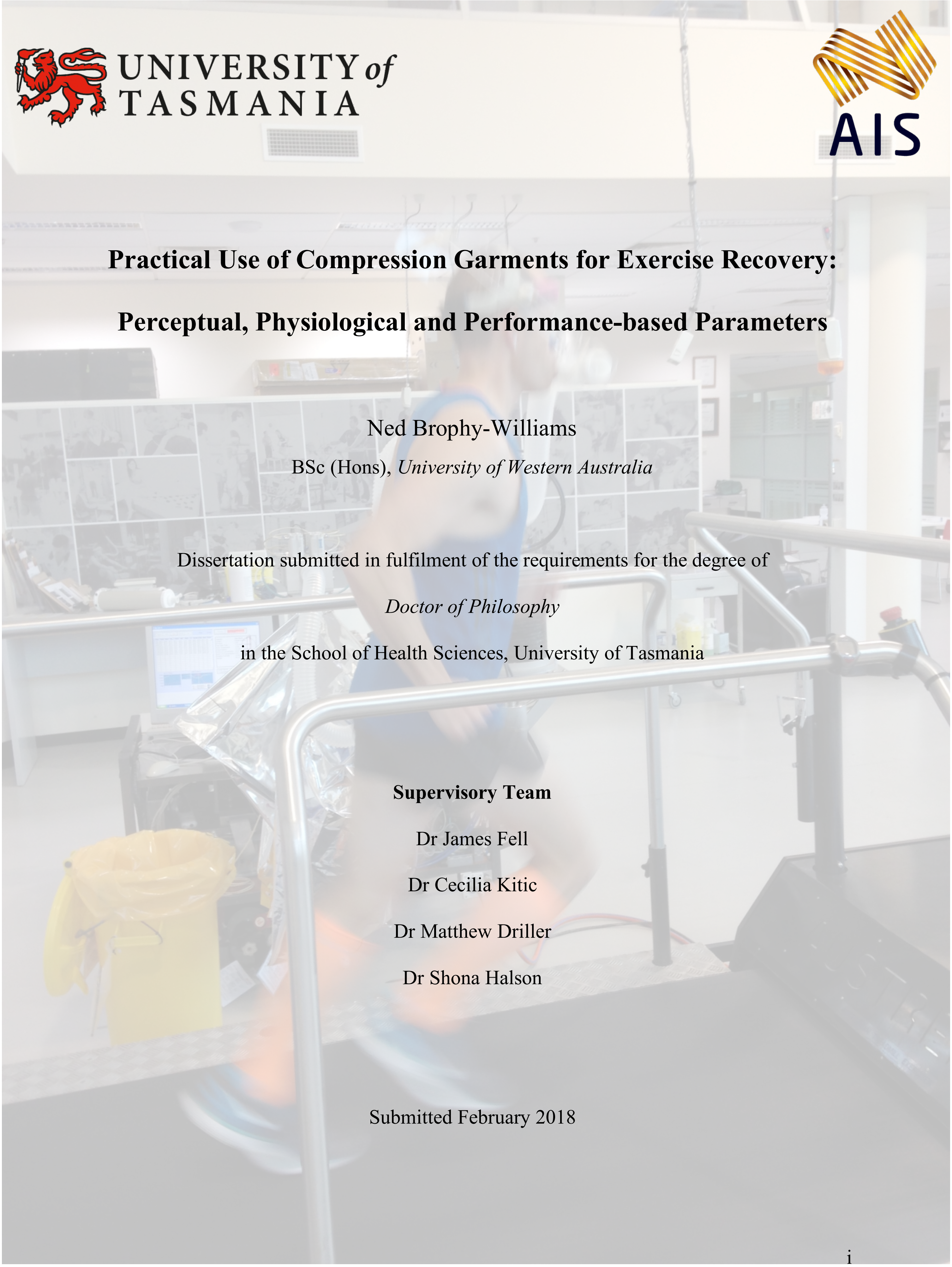

UNIVERSITY of TASMANIA

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Practical Use of Compression Garments for Exercise Recovery: Perceptual, Physiological and Performance-based Parameters

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BSc (Hons), *University of Western Australia*

Dissertation submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

in the School of Health Sciences, University of Tasmania

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Submitted February 2018

Declaration of Originality

I hereby declare that this thesis entitled *Practical Use of Compression Garments for Exercise Recovery: Perceptual, Physiological and Performance-based Parameters* contains no material which has been accepted for a degree or diploma by the University of Tasmania or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material has previously been published or was written by another person except where due reference is made in the text of the thesis, nor does the thesis contain any material that infringes Copyright Act 1968.

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The following people and institutions contributed to the publication of work undertaken as part of this thesis:

1. Ned Brophy-Williams (candidate), University of Tasmania
2. Dr James Fell (primary supervisor), University of Tasmania
3. Dr Cecilia M Kitic (supervisor), University of Tasmania
4. Dr Matthew W Driller (supervisor), University of Waikato
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Paper 1: Evaluating the Kikuhime pressure monitor for use with sports compression clothing, *Sports Engineering*, 2014; 17(1):55-60.

- Located in Chapter 2
- Candidate (1) was the primary author and contributed to 80% of the planning and execution of the research project and subsequent publication.
- Authors 2, 3 and 4 contributed to the conceptualisation of the research design.
- Author 4 contributed significantly to the execution of laboratory trials.
- Authors 4 and 5 contributed to the data analysis.
- All authors contributing to the drafts of the manuscript.

Paper 2: Confounding compression: The effects of posture, sizing and garment type on measured interface pressure in sports compression clothing, *Journal of Sports Sciences*, 2015, 33(13):1403-10.

- Located in Chapter 4

- Candidate (1) was the primary author and contributed to 80% of the planning and execution of the research project and subsequent publication.

- All authors contributed to the conceptualisation of the research design.

- Author 4 contributed significantly to the execution of laboratory trials.

- Authors 3 and 4 contributed to the data analysis.

- All authors contributing to the drafts of the manuscript.

Paper 3: Effect of compression socks worn between repeated maximal running bouts, *International Journal of Sports Physiology & Performance*, 2017; 12(5):621-7.

- Located in Chapter 6

- Candidate (1) was the primary author and contributed to 80% of the planning and execution of the research project and subsequent publication.

- All authors contributed to the conceptualisation of the research design.

- Author 4 contributed significantly to the piloting and execution of laboratory trials.

- All authors contributed to the data analysis and to drafts of the manuscript.

Paper 4: Wearing compression socks during exercise aids subsequent performance, *Journal of Science and Medicine in Sport*, 2018; (In Press).

- Located in Chapter 7

- Candidate (1) was the primary author and contributed to 80% of the planning and execution of the research project and subsequent publication.

- All authors contributed to the conceptualisation of the research design.

- Author 4 contributed significantly to the piloting and execution of laboratory trials.

- All authors contributed to the data analysis and to drafts of the manuscript.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published manuscripts contributing to this thesis.

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Statement of Contribution to Thesis

The thesis comprises six research investigations which have been completed almost entirely by the candidate, Ned Brophy-Williams.

- Ned Brophy-Williams (School of Health Sciences, University of Tasmania): Study design, lead role in recruitment, data collection, data analysis and interpretation, first author on all manuscripts (Chapters 2 to 7). However, the following people also contributed to each of the studies as detailed:
- James Fell (School of Health Sciences, University of Tasmania): Advised on study design, assisted with statistical analysis, manuscript preparation and revisions.
- Cecilia Kitic (School of Health Sciences, University of Tasmania): Advised on study design, assisted with statistical analysis, manuscript preparation and revisions.
- Matthew Driller (Faculty of Health, Sport & Human Performance, University of Waikato): Advised on study design, assisted with recruitment, pilot testing and data collection, statistical analysis, manuscript revisions.
- Shona Halson (Physiology, Australian Institute of Sport): Advised on study design, assisted with statistical analysis, manuscript preparation and revisions.

Statement of Ethical Conduct

The research associated with this thesis has been conducted in accordance with the requirements of the National Statement on Ethical Conduct in Human Research and abides by the guidelines of the Tasmania Health and Medical Human Ethics Research Committee of Tasmania: (Approval numbers: H0012847 and H0013539).

Ned Brophy-Williams 9 February 2017

List of Publications Arising from this Thesis

Brophy-Williams, N., Driller, M.W., Halson, S.L., Fell J.W. & Shing C.M. Evaluating the Kikuhime pressure monitor use with sports compression clothing. *Sports Eng.* 2014; 17(1):55-60.

Brophy-Williams, N., Driller, M.W., Shing, C.M., Fell, J.W., Halson, S.L. Confounding compression: the effects of posture, sizing and garment type on measured interface pressure in sports compression clothing. *J Sports Sci.* 2015; 33(13): 1403-10.

Brophy-Williams, N., Driller M.W., Fell, J.W., Halson, S.L., Kitic, C.M. Pressure gradient differences between medical grade and sports compression socks. *Sports Eng.* (under review).

Brophy-Williams, N., Driller, M.W., Kitic, C.M., Fell, J.W., Halson, S.L. Effect of compression socks worn between repeated maximal running bouts. *Int J Sport Physiol Perf.* 2017; 12(5):621-7.

Brophy-Williams, N., Driller M.W., Kitic, C.M., Fell, J.W., Halson, S.L. Wearing compression socks during exercise aids subsequent performance. *J Sci Med Sport*. 2018; (In Press).

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Driller, M.W., Brophy-Williams, N. The use of compression garments in Australian athletes: a survey. *J Athl Enhanc.* 2016; 5(3):1-4.

Conference Presentations

November 2012: Applied Physiology Conference (Melbourne, Australia), Graduated sports compression garments – uncovering the full story.

April 2014: 6th Exercise & Sports Science Australia Conference: Research to Practice (Adelaide, Australia), Poster: Brophy-Williams, N., Gliemann, L., Fell, J.W., Shing, C.M., Driller, M.W., Halson, S.L., Askew, C.D. Haemodynamic changes induced by sports compression garments and changes in posture.

November 2014: Applied Physiology Conference (Canberra, Australia), Compression socks for endurance performance – "Aren't they just a placebo?"

May 2015: American College of Sports Medicine Annual Meeting (San Diego, USA), Poster: Brophy-Williams, N., Driller, M.W., Shing, C.M., Halson, S.L., Fell, J.W. Physiological, perceptual and performance-based effects of compression socks –are they just a placebo?

Acknowledgements

First and foremost, my PhD supervisors. A huge thank you to Ceil and Dr J down in Tasmania. It’s been no mean feat to get this far, having not even visited Launceston since my confirmation of candidature in 2013!

James, you’ve been tremendous. Whether it’s chasing me up hills on a cold Launceston morning, inspiring your army of kids, or running the show down at UTas, your support has been second to none. From our first meeting in Tasmania, you’ve put me at ease, but at the same time, continued to challenge me. You’ve been awfully patient with a PhD student who is nearing the six-year mark. I do remember you warning me this could well happen when I left Canberra in 2015, but I knew I had your support whichever way I decided to go.

Ceil, in the time it’s taken me to finish my thesis, you’ve been married, had a kid and started a business (and this isn’t just a reflection of how long it’s taken me!). Your selfless, hard working attitude was a great motivator for me. Thank you for your enthusiasm and encouragement throughout.

To Matt, I still have a clear memory of when you stuck your head over the office cubicle back in 2012 to tell me you had something I might be interested in (the advertisement of my eventual PhD position). Little did I know that was only the beginning of such a big adventure. You were there at all the important times, helping to collect data, being a pilot guinea pig, and even a housemate. You taught me a lot along the way, about research and practice in elite sport, but also in life in general, for which I’m very thankful.

And to Shona, you’ve provided some fantastic opportunities for me across the journey, whether it was with 2XU, Rexona or the St Kilda Football Club. I have no doubt that these played a role in shaping me towards the position I am in today, so thank you.

To my family, Mum, Dad & Sambo, you’ve always been there to support me, to understand what on earth a PhD student’s days are filled with. Whether it was coming to visit in Canberra, or supporting from afar, you’ve provided more than I could ask for. Thank you.

To Cee, my loyal partner on this ride. Thank you for your understanding during the testing times. You’ve seen the whole journey from Canberra to Sydney and have been so good in helping me get to the end of the road.

And finally, to Grandad. I know that if you had the opportunity to go to university, you would have got stuck right in. Your interest and enthusiasm and continual “how’s that thesis going?” have been a driving factor behind my (eventual!) completion, and I’m really proud to be able to tell you that I’ve made it, and the thesis is now complete.

This piece of work will have my name on the front of it but wouldn’t be possible without the contributions from everyone I’ve mentioned here. Huge thanks to you all!

General Abstract

Background and Aims

Elite athletes are continually pursuing the small gains that may assist in improving their performance and edging them ahead of their opponents. Ergogenic aids, including a variety of sports equipment, are commonly employed to achieve such gains. One particular aid that is frequently utilised in an attempt to augment both exercise performance and recovery is sports compression garments.

Compression garments have long been used in a clinical setting to augment blood flow in patients with poor circulation. They are widely recognised as a beneficial and effective tool in this population. Extensive research findings have supported the capacity for compression garments to narrow blood vessels, increase both arterial and venous flow, and physically restrict the space available for oedema to form. These mechanisms reduce the incidence of deep vein thromboses, limb swelling and venous ulcers.

The transfer of these physiological enhancements to an athletic population manifests in reduced limb swelling, removal of metabolites and improved nutrient delivery to the muscles. These mechanisms are proposed to aid performance by improving recovery and delaying fatigue. Further to these potential physiological adaptations, sports compression garments are also proposed to influence athletic performance via reductions in muscle oscillation and improved proprioception. In addition, the commonly held belief in the efficacy of sports compression garments to enhance performance also has the capacity to affect athletic outcomes.

To better understand the capacity of compression garments in a sporting setting, and link together the multiple mechanisms they have the potential to induce, this thesis first sought to

characterize the physical properties of sports compression garments. Subsequently, an investigation was conducted to assess whether sports compression garments worn by an athletic population could influence blood flow and limb volume in a manner similar to that of clinical patients. Progressing from this mechanistic study, two further investigations measured the impact compression socks had on initial performance, recovery and subsequent performance when worn either during or post-exercise. These latter studies incorporated perceptual, psychological, physiological and performance-based outcomes assessed, given the multi-factorial mechanisms proposed to underlie the benefits of compression. In combining the findings of these investigations, this thesis aimed to improve the understanding of the potential connections between primary, secondary and tertiary based outcomes so as to better comprehend any changes that are induced by the use of sports compression garments (Figure 1).

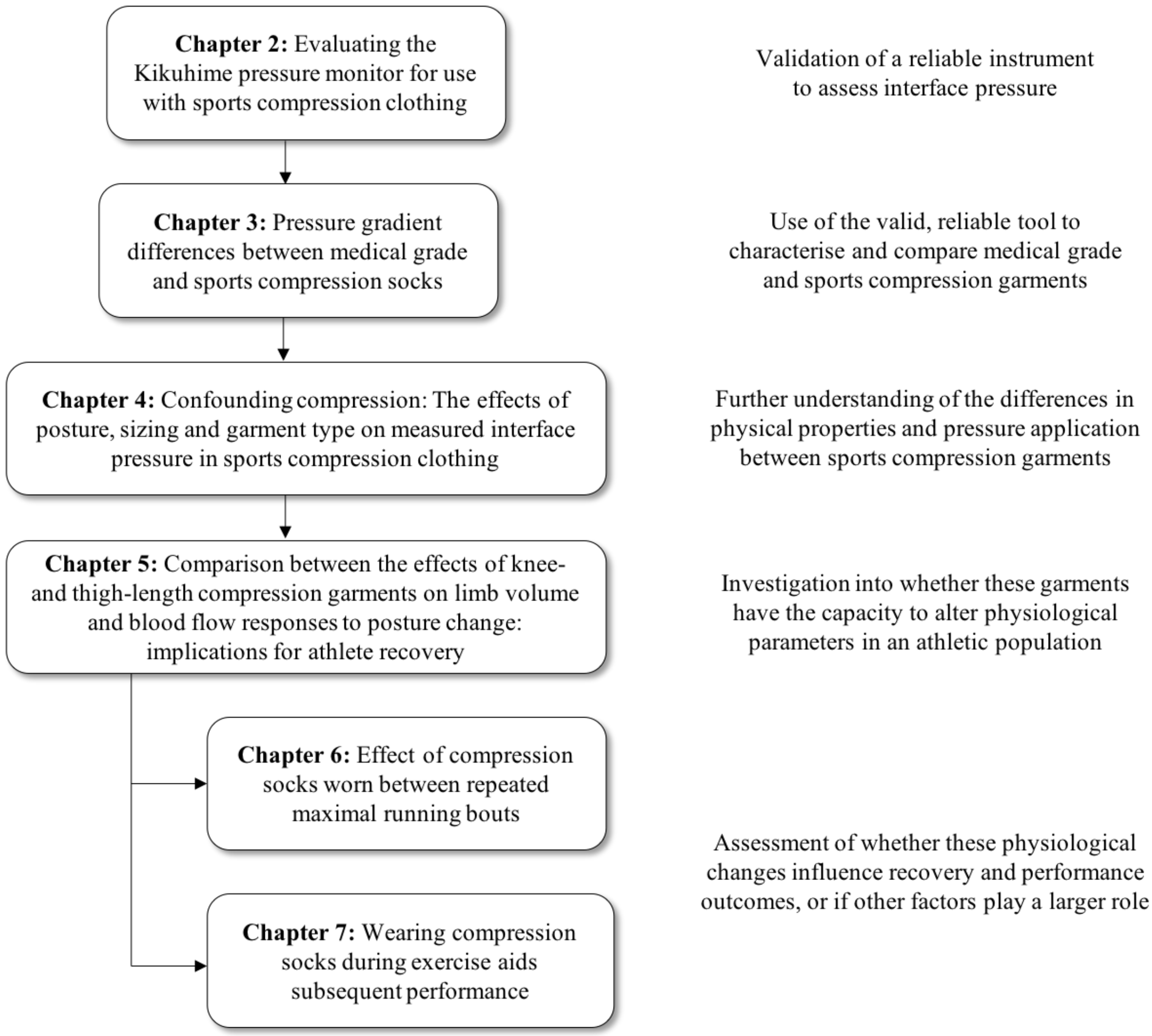

Figure 1. Schematic of the thesis structure.

Methods and Results

A valid, reliable pressure monitoring device was required to accurately assess properties of the compression garments under investigation throughout this thesis. A water column was used as a gold standard to assess the validity of the Kikuhime pressure monitoring device, a portable tool capable of providing continuous pressure measurements. Repeat measures taken by multiple investigators were used to evaluate the system's reliability. The Kikuhime monitor was found to be accurate within a range of pressures likely to be measured in sports compression garments (5-100mmHg, mean intra-class correlation=0.996). Favourable results were also found on the capacity for measures taken by the monitoring device to be repeatable, both within and between investigators (typical error; mean ± SD: 1.3 ± 0.9mmHg and 1.8 ± 0.9mmHg, respectively). It was therefore considered a valid and reliable tool, fit for use in further investigations.

A trial was then conducted to assess any differences apparent between medical grade and sports compression garments, with the intention of discovering whether the two garments exhibit similar physical properties. Sixty (30 male, 30 female) national representative athletes were fitted with both medical grade and sports compression socks before the Kikuhime pressure monitor was used to measure interface pressure at three landmarks across the lower leg. Medical grade compression socks were found to exert a *small*, yet significantly higher mean pressure across the three landmarks (mean ± SD: 28.8 ± 4.4mmHg) than sports compression socks (26.3 ± 4.0mmHg, $p<0.001$, $d=0.57$). It is unlikely, but remains to be seen whether this pressure differential is large enough to induce any difference in physiological response. Of interest, both garments exhibited a reverse pressure gradient, with highest pressures applied at the proximal end of the garment. These pressure profiles contrast with the commonly accepted belief that graduation of pressure (higher to lower, distal to proximal) is required for blood flow augmentation; but do reflect highest pressures being applied to large muscle bellies, which is most likely in order stimulate any underlying physiological changes.

To better understand the influence that different garment types, garment sizes and athlete posture have on pressure application, eighteen athletes were recruited to assess differences between sports compression tights and compression leggings. Both garments were fitted according to manufacturer's guidelines for assessment, along with measures taken while wearing garments one size larger and one size smaller than recommended. Pressure applied by this range of sizes and garments was assessed in three postures; standing, sitting and lying. After pressure measurement at six landmarks across the length of the lower limb, compression leggings were found to exert significantly higher pressure than compression tights (mean pressure ±95%CI; 18.9 ±1.6mmHg and 13.0 ±1.2mmHg respectively, $p<0.001$). This was likely attributable to fabric construction. Further to this result, posture influenced pressure application, with pressure highest when standing ($p<0.001$). As expected, oversized compression tights exerted a lower mean pressure than those fitted according to recommendations and undersized garments (mean pressure ±95%CI; 10.4 ±1.0mmHg, 13.0 ±1.2mmHg and 13.8 ±1.2 respectively, $p<0.001$). No differences were found between sizes for sports compression leggings.

Once the physical properties of sports compression garments were rigorously assessed, an investigation into the capacity for different garments to influence physiological parameters was conducted. Eighteen physically active males were recruited to partake in three different trials: one involved wearing a sports compression legging (LEG), one with a sports compression sock (SOCK) and a control condition with no compression garments used (CON). Each trial consisted of participants lying supine while resting arterial flow measures were taken using venous occlusion plethysmography and Doppler ultrasound imaging of the femoral artery. They were then tilted to an upright position (60°) for five minutes, before returning to supine for a further five minutes, with measures of whole limb volume, acute arterial flow, heart rate, respiratory rate, blood pressure and interface pressure collected throughout the tilt protocol. When exposed to orthostatic stress, calf volume in SOCK increased more than any other condition ($p<0.01$), but this was followed by a greater reduction in limb volume when returned to supine. Limb volume changes were similar between LEG and CON, possibly explained by an increased respiratory rate in CON ($p<0.01$) compensating for additional cardiovascular strain applied when compression garments were not worn. These findings imply that sports compression socks may be effective in reducing swelling post-exercise.

To determine efficacy in a performance-based environment, sports compression socks were then worn by athletes for an hour between repeated five kilometre running time trials. Twelve well-trained participants (mean 5km run time ± SD; 19:29 ± 1:18 min:sec) completed trials both with and without compression socks between running bouts (COMP and CON, respectively). Split times, 3D scans for changes in limb volume and perceptual measures of fatigue, soreness and recovery were assessed, as well as the athletes' perceptions on the efficacy of the garments taken into account. Performance in COMP was similar between time trials (mean **Δ** ± SD; 5.3 ± 20.7s, d=0.07, p=0.20) while for CON, performance significantly decreased in the second time trial (mean **Δ**; 15.9 ± 13.3s, d=0.19, p<0.01). Further analysis revealed that participants who believed that compression garments could aid their recovery (n=7) had subsequent performance further enhanced than those who did not believe in their efficacy (mean **Δ**; -3.6 ± 19.2s, d=0.05, p=0.32, and 17.9 ± 17.0s, d=0.19, p=0.04, respectively). Unrelated to participant beliefs, cross-sectional area of the calf and perceptions of muscle soreness were both reduced after using COMP (p<0.01). These results display a multi-dimensional approach to understanding how compression socks positively influence exercise recovery and subsequent exercise, and the potential that multiple mechanisms may influence these outcomes.

The effect of wearing compression garments during exercise on subsequent performance was then investigated. Following a similar testing protocol to the previous study, twelve male runners completed two trials of repeat five-kilometre time trials, one wearing sports compression socks during the initial exercise bout (COMP) and one with no compression garments (CON). The same range of variables were assessed, as well as oxygen consumption and blood lactate during the standardised warm up before each time trial. The decline in run performance in CON from first to second time trial was *moderate* and significantly greater than that experienced by runners in COMP (9.6 ± 10.4s, d=0.67, p<0.01). No differences were found between trials for initial performance, oxygen consumption, blood lactate, calf volume or perceptions of muscle soreness, fatigue or recovery p=0.18-1.00). Similarly, none of these parameters were influenced by participants' belief in the likelihood that compression garments would aid performance. The capacity for compression garments worn during exercise to impact subsequent performance is a novel finding from this investigation, as there has previously been little focus on this aspect of their use. In addition to the novelty of this finding, this study poses further questions as to which underlying mechanisms are at play to invoke such performance changes.

Conclusions

This progression of investigations adds important breadth and depth to the sports compression garment literature. Although a vast number of investigations have taken place in the field, this thesis has highlighted, and aimed to address, several deficiencies. A valid, reliable tool for effective pressure assessment has been identified, forming part of the foundation required for rigorous compression garment research. An appreciation for potential differences between medical grade and sports compression garments has been highlighted, although it remains to be seen whether such a small pressure differential has a meaningful impact on subsequent outcomes. In addition to this garment comparison, an evaluation of different types of sports compression garments, garment sizes and postures adopted during assessment, has further illustrated the importance of standardising and reporting pressure measurements in any future sports compression research.

The capacity for sports compression socks to aid in reducing limb volume, and therefore potentially aiding recovery, was demonstrated. This finding was reinforced in a practical setting, with compression socks worn during and post-exercise both augmenting subsequent performance. The assessment of a variety of parameters allowed a better understanding of the factors contributing to such performance changes, such as reduced limb swelling, improved perceptual responses and athletes' beliefs.

Based on the findings from this series of experiments, sports compression garments are a valid ergogenic aid, with the potential to aid both subsequent performance and recovery when worn during and post-exercise.

Table of Contents

List of Tables

List of Figures

Common Abbreviations

AF	Arterial Flow
BLa	Blood Lactate
CI	Confidence Interval
CON	Control trial
COMP	Compression intervention
CSA	Cross Sectional Area
CV	Coefficient of Variation
HR	Heart Rate
ECG	Electrocardiogram
ICC	Intra-Class Correlation
LEG	Sports Compression Legging
MAP	Mean Arterial Pressure
MS	Muscle Soreness
RR	Respiratory Rate
SD	Standard Deviation
SOCK	Sports Compression Sock
TEM	Typical Error of Measurement
TQPR	Total Quality Perceived Recovery
TT	Time Trial
VC	Vascular Conductance
VOP	Venous Occlusion Plethysmography

Chapter 1: Literature Review

Introduction

Success in elite sport requires the pursuit of all possible legal means of enhancing performance and recovery. Athletes and sports practitioners seek ergogenic aids with the potential to achieve these aims, with sports compression garments proving to be a popular tool[1-3]. The use of compression garments is widespread amongst athletes of all sports[4], despite investigations into their efficacy producing mixed results[3,5]. Compression garments are widely recognised to aid in recovery post-exercise[6,7], but their capacity to influence athletic performance remains equivocal[3], and any links between changes in performance or recovery and their underlying mechanisms are unclear.

The use of compression garments originates in a clinical setting, where patients seeking improvements in circulation have reaped their benefits for over 60 years[8]. Compression garments have been used to augment blood flow, reduce oedema and prevent deep vein thromboses and venous ulcers[9-12]. The potential for compression garments to induce these physiological changes has seen them adapted to sporting environments under the premise that these alterations may improve athletic performance. These improvements are proposed to be a result of reduced muscle damage and swelling[6], enhanced exercise economy[13], removal of metabolites[14] and increased delivery of oxygen-rich blood[15]. However, it isn't clear yet whether benefits seen in clinical patients may transfer to healthy athletes[5].

The scope of this literature review will cover the physical properties of sports compression garments to the physiological alterations that they may induce, culminating in the combination of these parameters and how they have the potential to influence exercise recovery. Identification of the gaps in these key areas will allow for a clear research direction to better understand the role of compression garments in an athletic setting, and why previous investigations may have produced equivocal findings.

Assessment of optimal pressure

To comprehend the potential impact of compression garments, we must first assess the level of compression being applied by each garment. Although recently recognised as a vital aspect of research in the area[16], the majority of investigations have not reported interface pressure applied by the garments they have tested[17]. Assessment of interface pressure allows transparent observations and comparisons between research studies in this area. To achieve such robust research, an accurate and reliable tool is required to assess interface pressure.

The Kikuhime pressure monitoring device is once such popular instrument that has previously been used to measure interface pressure with compression clothing. It is recognised as an established, portable pressure monitoring device[18], making it preferred by scientists and practitioners. The device has been reported to be valid when assessed using methods such as a pressurised chamber, a blood pressure cuff encapsulating a rigid cylinder, and a water column exerting pressures up to 30mmHg[18-20]. Research papers to have produced findings in favour of the device's validity have reported a global error of 3.1-4.0%[18,19]. However, the application of these validity studies to a sporting setting is limited as they have not used a 'gold standard' technique to assess a range of pressures reflective of those previously reported in the sports compression literature[21]. A water column can be considered as a 'gold' standard for pressure measurement as it does not require calibration using another tool, therefore minimising the potential for additional noise to be incorporated in validity measures. Consequently, this method should be used to assess a range of pressures greater than those reported in previous sports compression literature to allow researchers to have greater confidence in the device's accuracy.

Once determined as accurate, a device used for pressure assessment must also exhibit reliability when tested in an environment reflective of that in which it will be used for further research. This allows researchers to confidently compare measures recorded across multiple tests by different investigators. To replicate future testing environments, assessment of device reliability requires measures to be collected from human limbs underneath sports compression garments[19]. Although previously reported to be reliable (coefficient of variation = 3.1-4.2%)[18,19], measurements in these investigations have not been collected *in situ*, rather by using rigid cylinders and pressure cuffs used for pressure measurements, bringing into question the transfer of reliability to assessments taken on human limbs.

The rigorous assessment of the validity and reliability of a portable pressure monitoring device prior to using it for measurements in further research will allow for a better understanding of the accuracy of the tool, as well as any potential noise in the measure, and how this should be taken into account when interpreting study findings.

Compression garment pressure and gradients

Many of the proposed benefits of sports compression garments relate to underlying physiological mechanisms that have been explored using medical compression garments applied to clinical populations[9,10]. However, it is yet to be investigated whether sports and medical grade compression garments demonstrate similar physical properties. Medical compression garments have been designed to elicit physiological alterations, while sports compression garments are more likely to be engineered for consumer comfort. It can therefore be assumed that sports compression garments would require similar physical properties to medical grade garments if they are to provoke similar physiological changes.

Research investigating the effect of varying pressure levels in compression garments have highlighted the capacity for higher pressures to alter physiological parameters and sports performance outcomes[17]. Moderate and high pressure stockings (25-46mmHg) are reported to significantly increase flow velocity in the popliteal vein compared to low pressure stockings (10-12mmHg) in healthy adult women[22]. Similarly, the recovery of muscle strength has been reported to be improved when compression tights with a higher pressure (mean pressure = 19.5mmHg) are worn post-exercise, compared to low pressure garments (11.5mmHg)[17]. These findings emphasise the need to have a clear understanding of the physical properties of the compression garments used in any research project, so that variations in pressure are not a component that can confound results.

Medical garments are commonly rated to an international standard criterion, such as that produced by the European Committee for Standardization[23], but sports compression garments have no such stringent classification parameters to meet. To better understand the likelihood of sports compression garments eliciting the same physiological alterations provided by medical grade garments, an objective assessment of the two must be carried out. Characterising the properties of both garment types will allow a better understanding of whether sports compression garments indeed demonstrate similar properties to medical compression garments, before any further comparisons are made on their capacity to elicit proposed benefits.

Garment types, sizes and postures

A range of different garment types are prevalent in the compression literature, from socks to tights and long-sleeved tops[24-26], all commonly used by athletic populations[4]. This variety of garments, alongside garment sizing, athlete posture, the range of locations used for pressure measurements and the actual pressure exerted, have been considered as contributing factors to the heterogeneous results when investigating the potential effects of sports compression garments[27].

The majority of research in the area has used garments fitted according to manufacturer's guidelines[6,28,29], without assessing interface pressure applied to each individual[17,30]. This deficiency makes the comparison of investigations with contradictory results very difficult as pressure variations are likely to occur within these sizing brackets. As previously mentioned, garments that apply a higher pressure can result in different physiological and performance outcomes when compared to those exerting lower pressures[17,22,31]. One method in achieving this pressure differential has been to fit study participants with garments one size smaller than the manufacturer's recommendation[32], which highlights the need to consider garment sizing and pressure application when conducting compression garment research.

An understanding of the impact of athlete posture on pressure application also plays an integral role in comprehending the myriad of factors that can influence interface pressure. The shift from supine to sitting to standing has been recognised as eliciting muscle flexion, which has been shown to increase interface pressure[33]. Partsch and colleagues also reported that a change in posture from supine to standing has the tendency to distort tissue, which in turn affects pressure application[34]. These investigations highlight the importance of standardising posture when assessing interface pressure, or at least make the reporting of posture during measurement a required inclusion in research papers.

Pressure measurement landmarks also need to be standardised to allow for consistent reporting of results in the sports compression literature. Measurement standards are in place for testing medical compression garments[23], but no such rigid guidelines exist, or have been applied, in an athletic setting. Although mid-calf and mid-thigh measurements are common landmarks for assessment[32,35], a greater range of sites across the lower limb would enhance the understanding of pressure application and any pressure gradients applied by sports compression garments. Such landmarks should consider the need to target the muscle belly, rather than bony tissue, to further increase their relevance.

Further research should target the assessment of pressure application *in vivo* of a range of different sports compression garments, of multiple sizes, in various postures, so as to better comprehend the influence that these factors have on the mechanical properties of the garment.

Physiological changes in athletes wearing compression garments

The capacity for compression garments to induce physiological changes in athletic populations, such as augmented limb blood flow and reduced limb volume, is largely unknown[36,37]. Extensive research into the use of compression garments in clinical or sedentary populations has highlighted their capacity to improve circulation and reduce oedema[9,10], but it remains to be seen whether these benefits transfer to athletes.

There are three levels of potential mechanisms induced by compression garments. These include primary mechanisms, such as the narrowing of blood vessels and the restriction of space available for swelling; secondary, including improved removal of metabolites[38] and delivery of nutrients and reduced swelling and muscle damage; and tertiary, such as improved recovery and enhanced subsequent performance[14,26] (Figure 1.1).

Changes in circulation brought about by compression garments originate with the application of garments increasing tissue pressure. This alteration reduces the pressure differential between tissues and blood vessels, allowing blood flow to be redirected to deep veins[39], with veins narrowing, resulting in increased flow velocity[34]. As a consequence of increased velocity, both arterial and venous flow are augmented[9,39]. These primary mechanisms are proposed to improve the delivery of oxygen-rich arterial blood to the fatigued muscles[15], in addition to hastening the removal of metabolites accumulated during exercise[14,38,40]. Further to these potential performance-enhancing alterations, increased venous flow may also aid in reducing limb swelling[41]. Together, these secondary mechanisms have the potential to impact subsequent exercise performance by accelerating the body's return to homeostasis[41], reducing muscle soreness[6,24] and improving perceptions of exercise recovery[42,43].

The physical capacity for compression garments to restrict space around the body has also been recognised as a key mechanism in reducing oedema in clinical populations[26]. The transfer of this mechanism to a sporting setting manifests in the reduction of swelling post-exercise, a secondary mechanism[1]. Athletes that have reported lower muscle soreness and improved perceptions of recovery are likely to be the benefactors of this reduced swelling[24,44].

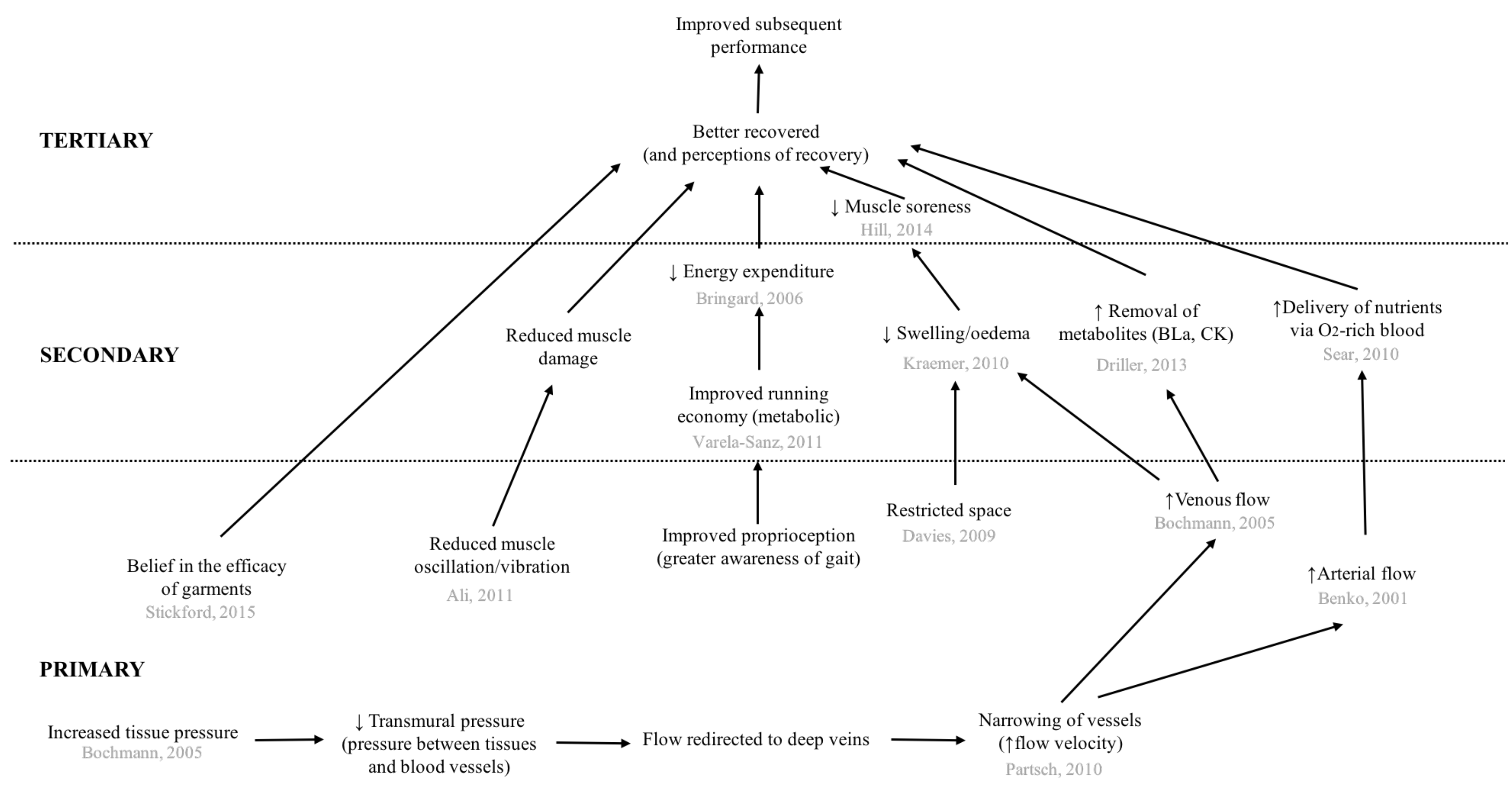

Figure 1.1 The myriad of mechanisms hypothesised to be evoked by sports compression garments categorised into primary, secondary and tertiary outcomes. Compiled from relevant studies in the compression garment literature[6,13-15,21,26,34,39,41,45-47].

Although these secondary physiological mechanisms have the potential to influence sports performance and recovery, evidence of their underlying primary mechanisms is sparse in athletic populations. One of few studies to have investigated healthy populations, Fuji and colleagues[48] reported augmented arterial flow to the forearm when wearing upper body compression. In contrast, healthy participants fitted with compression socks have reported to display no change in popliteal artery flow, or more global haemodynamic measures such as heart rate and blood pressure[37]. Similarly, the venous pumping action has been reported to be unaffected by compression garments when worn by male athletes[49].

These varied findings suggest that it is unknown whether athletes have the capacity for blood flow and other haemodynamic parameters to be altered by sports compression garments[37]. Improving our understanding of how blood flow and the formation of oedema may be influenced by compression garments worn by athletes will assist in comprehending any performance outcomes affected by these alterations. Future research needs to focus on rigorous assessment of these primary physiological mechanisms, rather than surrogates such as heart rate and blood lactate, with precision required in incorporating measures of both acute and whole limb blood flow, as well as changes in limb volume, as it is likely that these changes will be quite small in athletic populations.

Compression for post-exercise recovery

Compression garments are widely recognised as beneficial to athlete recovery[1,2,5,7]. Reductions in muscle soreness, enhanced perceptions of recovery and enhanced subsequent performance have been reported following their use[1,3] (Table 1.1). However, there has rarely been a clear connection elucidated between these tertiary outcomes and the underlying secondary mechanisms, with links to primary mechanisms even less common (Figure 1.1). The aforementioned secondary mechanisms include improvements in running economy, reduced swelling, and augmented removal of metabolites. Primary mechanisms range from physiological alterations, such as augmented blood flow and reductions in oedema, to more technically-oriented parameters such as improved proprioception and reduced muscle oscillation, as well as psychological factors, like athletes' expectations for the efficacy of the garments.

Table 1.1 Summary of pertinent literature assessing the use of sports compression garments worn post-exercise.

Study	Garment Type	Subjects	Activity	Key Mechanisms/Outcomes		
				Primary	Secondary	Tertiary
Bieuzen, 2014[24]	Socks	11 athletes (11m)	Running (15.6km trail)		↔ HR, CK	↑ jump performance ↔ running performance, perceived fatigue ↓ muscle soreness
Carling, 1995[50]	Arm sleeves	23 healthy (16m, 7f)	Resistance training (eccentric exercise)		↔ upper limb volume	↔ muscle soreness, range of motion, peak torque
Davies, 2009[26]	Tights	11 athletes (7f, 4m)	Sprints, agility and jumps following drop jumps		↔ CK, LDH, lower limb volume	↔ athletic performance ↓ muscle soreness
de Glanville, 2012[51]	Tights	14 athletes (14m)	Cycling (40km time trial)		↔ oxygen consumption, BLa	↑ power output ↔ perceived exertion
Driller, 2013[14]	Tights	10 athletes (unknown)	Cycling (30min, including 15min time trial)		↓ BLa, limb volume	↑ power output ↔ muscle soreness
Duffield, 2007[44]	Whole body	10 athletes (10m)	Running (30x20m repeated sprints)		↓ CK	↓ muscle soreness
Duffield, 2010[42]	Tights	11 athletes (unknown)	Running (10x20m sprints and 10 bounds)		↔ HR, BLa, CK, CR-P, pH	↔ sprint & bounding performance ↓ muscle soreness

Study	Garment Type	Subjects	Activity	Key Mechanisms/Outcomes		
				Primary	Secondary	Tertiary
Goto, 2014[52]	Whole body	9 athletes (9m)	Resistance training (3-5 x 10 reps of 9 exercises)		↔BLa, inflammatory blood markers ↓ limb volume	↑ upper body strength, lower body strength ↓ muscle soreness
Hamlin, 2012[53]	Tights	22 athletes (22m)	Team sport (84min rugby simulation)			↑ 3km run performance, sprint performance ↓ muscle soreness, perceived fatigue
Hill, 2014[54]	Tights	24 athletes (17m, 7f)	Running (marathon)		↔CK, C-reactive protein	↓ muscle soreness
Hill, 2017[17]	Tights	45 athletes (26m, 19f)	Jumps (100 drop jumps)		↔CK, C-RP, myoglobin ↓ AST	↑ jump performance, leg strength ↔muscle soreness
Miyamoto, 2014[55]	Shorts	11 athletes (11m)	Running (34.5min submaximal treadmill)		↓ skeletal muscle proton transverse relaxation time	↓ muscle fatigue
Pruscino, 2013[43]	Tights	8 athletes (8m)	Team sport (75min field hockey simulation)		↔CK, C-RP	↑ perceived recovery ↔jump performance ↓ muscle soreness
Sperlich, 2013[56]	Shorts	6 healthy (6m)	Cycling (incremental test to exhaustion)	↓ muscle blood flow	↔glucose uptake	↔elbow flexor peak torque

*HR=heart rate, CK=creatine kinase, LDH=lactate dehyrogenase, BLa=blood lactate, C-RP=C-reactive protein, AST=aspartate transaminase, m=males, f=females

↑ indicates significant improvement in this parameter, ↔indicates no change in this parameter, ↓ indicates significant decline in this parameter

Sports compression garments are commonly found to positively influence perceptual responses. Reductions in muscle soreness have been reported when wearing compression garments after trail running, marathon running, repeated sprints, resistance training and team sport simulations[24,43,44,52-54] (Table 1.1). Similarly, athletes wearing compression garments after running and team sport exercise have reported lower perceptions of fatigue and improved perceptions of recovery[43,55]. These improved perceptual responses may be a contributing factor to enhanced subsequent exercise performance.

However, the capacity for sports compression garments to aid subsequent performance when worn post-exercise is far from clear (Table 1.1). Several investigations have reported compression garments to aid in improving jump performance, cycling power output, 3km running performance, sprint speed, upper and lower body strength when worn following trail running[24], cycling[14,51], team sport activity[53], resistance training[52] and muscle damage-inducing drop jumps[17]. In contrast, research has found no impact on jump performance, sprinting and bounding, or peak muscle torque when wearing compression after team sport activity[43], running[42] and eccentric resistance exercise[50]. Several factors are likely to have contributed to the disparity between these outcomes, with the capacity for compression garments to induce their proposed underlying mechanisms likely to play a part. Both athletic performance and perceptual responses can be considered tertiary outcomes produced by the use of compression garments. Although the majority of investigations have reported favourably on these tertiary outcomes, few have linked them to primary or secondary mechanisms evoked by compression garments (Figure 1.1).

Blood lactate and inflammatory blood markers are secondary mechanisms, but rarely seem to be affected by the use of compression[17,24,26,42,43,52,54]. Similarly, a reduction in limb swelling is an indicator of primary mechanisms in action, although findings from investigations involving healthy populations have been mixed. Born and colleagues' review[1] reported compression garments to have a moderate effect on the reduction of muscle swelling, yet Montgomery[57] and Davies[26] both reported no impact on thigh and calf girth when garments were worn post-exercise. This lack of consistency between alterations in secondary physiological mechanisms and tertiary outcomes suggests that compression garments may influence exercise performance by alternate means.

One potential manipulator of research outcomes that has emerged is participants' belief in the efficacy of compression garments. The belief effect is particularly pertinent to compression garment research as a true placebo trial is not achievable in this area, providing opportunity for study outcomes to be influenced by participants expectations[46]. Athletes have previously been shown to better maintain power output when completing a series of maximal jumps wearing compression tights compared to a trial without compression garments, with authors acknowledging that all participants perceived the garments were aiding them, and that this may have influenced results[58]. In support of this theory, Stickford and colleagues[46] found no difference in group means when assessing the effect of compression socks on running economy; however, highly individual responses were noted by the authors. Those participants who had previously used calf compression sleeves and believed in their efficacy exhibited the greatest improvements when wearing the garments in experimental conditions. Similar changes aligned with athlete expectancy have previously been reported in other areas of performance[59], with one particular investigation outlining how an individual's perception of recovery strongly correlates with subsequent performance, an area highly relevant to the use of compression garments[60], further highlighting the importance of considering the belief effect in future research.

The majority of research studies in the area of sports compression have explored the capacity for compression garments to augment performance when worn during exercise, or to improve recovery when worn post-exercise. To the authors' knowledge, no investigations have aimed to illustrate the effect of wearing compression garments during exercise on subsequent exercise performance. The potential for sports compression garments to aid blood flow and reduce muscle damage during exercise, resulting in enhanced recovery, may lead to improvements in subsequent performance.

A multi-faceted approach is required to provide further context to any changes that compression garments bring about when worn post-exercise. Investigations should include assessment of primary, secondary and tertiary outcomes during initial performance, recovery and subsequent exercise to better understand the possible connection between physical, psychological and performance-based parameters.

Compression for exercise performance

Compression garments are also commonly worn during exercise under the premise that they have the potential to improve performance[3]. Much like investigations targeting the use of compression garments post-exercise, research into this area has resulted in mixed findings. Again, there has often been a disparity between performance outcomes and their underlying mechanisms.

Wearing compression garments during exercise has been reported to improve repeated sprint performance[61], aerobic and anaerobic running thresholds[62], submaximal running[45], 400m sprints[63], jump capacity[64], team sport performance[65] and technical skill accuracy[66] (Table 1.2). Conversely, several investigations have concluded that compression garments have no impact on performance when worn during exercise, including no change in running performance; whether it be 10km[21,67], marathon[68], half ironman triathlon[69] or trail running[70]; and no influence on kayaking[25], jumping[71,72], cycling[73] or skiing[74] performance, nor change to power output during resistance exercises[75,76]. Furthermore, Rider and colleagues[77] even reported a negative influence of compression socks on performance in a graded treadmill test. This mix of tertiary outcomes begs the question of how they relate to underlying mechanisms (Figure 1.1). A greater understanding of the primary and secondary mechanisms, such as reduced muscle oscillation[78], improved proprioception[66] and augmented blood flow[45], and their relationship with these tertiary outcomes, would add further context and perhaps some rationale for previous heterogeneous findings.

Table 1.2 Summary of pertinent literature assessing the use of sports compression garments during exercise.

Study	Garment Type	Subjects	Activity	Key Mechanisms/Outcomes		
				Primary	Secondary	Tertiary
Ali, 2010[67]	Socks	10 athletes (9m, 1f)	Running (40min submaximal treadmill)		↔oxygen consumption, HR, BLa, CK, myoglobin	↔run performance muscle soreness
Ali, 2011[21]	Socks	12 athletes (9m, 3f)	Running (10km track)		↔HR, BLa	↑ jump performance ↔run performance
Areces, 2015[68]	Socks	17 athletes (15m, 2f)	Running (marathon)		↔CK, LDH, lower limb volume	↔run performance ↓ muscle soreness
Born, 2014[61]	Tights	24 athletes (24f)	Running (30x30m repeated sprints)		↔oxygen consumption, HR	↑ sprint speed ↓ perceived exertion
Bringard, 2006[45]	Tights	6 athletes (unknown)	Running (submaximal)		↔oxygen consumption	
Dascombe, 2011[25]	Long-sleeved top	7 athletes (5m, 2f)	Kayaking (incremental test)		↔oxygen consumption, HR, BLa, muscle oxygenation	↔kayak performance
Del Coso, 2014[69]	Calf sleeves	36 athletes (unknown)	Triathlon (half Iron-man)		↔CK, myoglobin	↔race time, jump height, perceived exertion, muscle soreness
Doan, 2003[71]	Shorts	20 athletes (10m, 10f)	Jumping (counter movement)	↓ muscle oscillation		↔jump performance
Driller, 2013[14]	Tights	12 athletes (12m) 12 athletes (12m)	Cycling (30min, including 15min time trial)		↔HR, BLa, lower limb volume	↔cycling time trial performance, muscle soreness
Faulkner, 2013[63]	Calf sleeves	11 athletes (11m)	Running (400m sprint)		↔BLa	↔run performance (400m) ↓ perceived exertion
Fu, 2014[72]	Shorts	12 athletes (12m)	Jumping (drop jumps)		↓ muscle activation	↔jump performance, force output

Study	Garment Type	Subjects	Activity	Key Mechanisms/Outcomes		
				Primary	Secondary	Tertiary
Higgins, 2009[65]	Tights	9 athletes (9f)	Team sport (60min netball simulation)		↔HR, BLa	↑ high speed distance covered ↔sprints, jump performance
Hooper, 2015[66]	Upper body	21 athletes (21m)	Golf and baseball (driving and pitching)			↑ driving and pitching accuracy
Kemmler, 2009[62]	Socks	21 athletes (21m)	Running (incremental test)		↓ BLa (↑ threshold pace) ↔VO2max	↑ run performance
Kraemer, 1998[64]	Shorts	40 athletes (20m, 20f)	Jumping (10 vertical jumps)			↑ mean jump performance
Martorelli, 2015[75]	Arm sleeves	15 athletes (15m)	Resistance training (6x6x50%1RM bench press)		↔BLa	↔power output, isometric strength
Pereira, 2014[76]	Arm sleeves	24 athletes (24m)	Resistance training (4x10 eccentrics)			↔power output
Rider, 2014[77]	Socks	10 athletes (7m, 3f)	Running (maximal treadmill)		↔oxygen consumption, HR, BLa	↔perceived exertion ↓ running performance
Sperlich, 2014[74]	Long-sleeved tops	10 athletes (10m)	Skiing (3x3min sprints)	↓ muscle oscillation	↓ BLa ↔oxygen consumption, HR	↔power output, perceived exertion
Vercruyssen, 2014[70]	Calf sleeves	11 athletes (11m)	Running (15.6km trail)		↔HR, BLa	↔run performance

*HR=heart rate, BLa=blood lactate, CK=creatine kinase, LDH=lactate dehyrogenase, m=males, f=females

↑ indicates significant improvement in this parameter, ↔indicates no change in this parameter, ↓ indicates significant decline in this parameter

The capacity for compression tights to reduce muscle oscillation is proposed to reduce energy expenditure, and therefore oxygen consumption[45]. Reductions in muscle movement have also been reported in conjunction with improved jumping performance[71]. Further, limiting muscle oscillation may lead to a reduction in muscle damage resulting from repetitive movements such as endurance running, therefore hastening recovery for subsequent exercise. This combination of factors may lead to sports compression garments yielding superior exercise performance. However, research in this area is yet to provide conclusive links between these mechanisms and eventual performance outcomes, with further rigorous investigations required to substantiate these hypotheses.

Improvements in proprioception have also been recognised as a potential benefit for athletic populations while wearing compression garments[21,66]. Tactile feedback produced by the garments can result in increased spatial awareness. This impact is largely limited to improvements in skill-based movements, such as baseball pitching and playing golf, and not changes in physiological parameters. However, Ji and colleagues[79] reported that fewer motor units were recruited for the same magnitude of force production when compression stockings were worn during an isokinetic strength exercise. This reduction in motor unit recruitment may allow for energy to be conserved in endurance events or possibly a reduction in neural fatigue. However, these concepts are also yet to be explored in detail, with additional evidence required before a strong link can be established with performance outcomes.

The potential for compressions garments to augment blood flow in an athletic population is reflected in research reporting a reduced energy cost for submaximal running[45]. However, these findings are fairly ambiguous, as conclusions have been made from surrogate assessment measures, such as oxygen consumption. Somewhat more direct measures, such as removal of blood lactate, have shown less promising results[21,25,63,67,77], while no changes have been reported when blood flow has been measured in the muscle[70]. These findings suggest that it is unlikely that blood flow is augmented by compression garments when worn during exercise, let alone whether any increase in arterial and venous flow would have the capacity to alter exercise performance.

Further research should endeavour to incorporate a multi-faceted approach to assessing the capacity of sports compression garments to influence performance when worn during exercise. This would ideally include measurement of psychological, physical and performance-based parameters, in addition to the effect on subsequent performance.

Summary

Although compression garments are widely used by athletic populations, there are still several facets that are yet to be explored in sufficient detail. These include accurate assessment of pressure application, an improved understanding of whether similar physiological adaptations are experienced by athletes as have been reported in clinical populations, and how physiological, psychological and performance-based parameters are influenced by their use both during exercise and for recovery.

Thesis Aims

This thesis provides an analysis of a number of areas of sports compression clothing research that are currently missing. The thesis begins with assessment of the reliability and validity of an instrument used to measure interface pressure, before using this instrument to explore any differences between the pressure applied by sports and medical grade compression garments. Further to this investigation, the variations in pressure application to the lower limb were explored extensively using different types of sports compression garments and a range of garment sizes across a spectrum of postures.

The mechanisms underlying any potential physiological benefits of sports compression garments were then investigated, with an athletic population recruited to determine whether acute or whole limb blood flow, or any of a myriad of haemodynamic parameters, would be augmented. Following this mechanistic investigation, performance-based experiments were conducted to better understand the efficacy of compression garments on both running performance and recovery, while taking into account the possible influence of physical and psychological parameters.

Chapter 2:

Evaluating the Kikuhime pressure monitor for use with sports compression clothing

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Running Title: Evaluating the Kikuhime pressure monitor

Total word count: 2 308

Abstract word count: 222

Number of Tables: 2

Number of Figures: 2

This chapter has been published as:

Brophy-Williams, N., Driller, M. W., Halson, S. L., Fell, J. W. & Shing, C. M., Evaluating the Kikuhime pressure monitor for use with sports compression clothing, *Sports Engineering,* 2014; 17(1):55-60.

Thomson Reuters Impact Factor (2017): 1.00

22 citations as at February 2018

Rationale

The physical characteristics of sports compression garments are rarely reported in the literature, making the comparison of study findings very difficult. Assessing interface pressure applied by garments would allow a better understanding of why such equivocal results have been reported in previous research. To achieve such an outcome, a valid, reliable pressure monitoring tool is required to collect this data. The Kikuhime is a portable pressure monitoring device that provides continuous pressure measurements, so it was selected to be evaluated for whether it was appropriate for use in further studies by assessing it's validity against a gold standard, and both its intra- and inter-tester reliability when used *in situ*.

Abstract

Introduction: Reporting accurate and reliable measures of pressure exerted by sport compression clothing assists in the interpretation and comparison of study findings. The objective of the current study was to assess the validity and reliability of the Kikuhime pressure monitoring device to measure the pressure of sport compression garments.

Methods: To assess validity, three separate Kikuhime sensors were compared to known pressures inside a water column, at 5mmHg increments ranging from 5-100mmHg. Intra- and inter-tester reliability was determined by comparing the results of two individuals performing five interface pressure measures at six different landmarks across the lower and upper leg of an athlete wearing sports compression leggings.

Results: All three sensors tested exhibited a very high intra-class correlation with the reference value (mean ICC=0.996). The typical error of measurement was low for both intra- and inter-tester reliability (mean ± SD: 1.3 ± 0.9mmHg and 1.8 ± 0.9mmHg, respectively). These results expressed as a coefficient of variation were 4.9 ± 2.4% and 7.4 ± 5.4%, respectively.

Conclusion: The findings from the current study suggest that the Kikuhime device is a valid and reliable instrument for use *in-situ* when measuring the pressure of sports compression garments in athletes assuming a static standing posture. The instrument could be used in future research involving compression garments to accurately quantify interface pressures and their subsequent effect on physiological and/or performance measures.

Keywords: interface pressure, in-situ, reliability, validity

Introduction

The use of compression garments and compression bandaging has been well documented in the medical literature as a method of treating circulatory and lymphatic disorders[5]. Given the efficacy of compression garments as a treatment in the medical field, the use of compression garments in the athletic industry has become increasingly popular over the past decade, with several commercial companies claiming that the associated medical benefits can be applied to enhance both recovery and performance in an exercise setting[73]. A substantial number of research papers have been published in both settings, however most exhibit a limitation in that they do not report interface pressure applied by the compression garments[80]. Many papers have merely relied on manufacturers' fitting recommendations and pressure application guidelines to estimate interface pressure levels[26,44,81].

The reporting of interface pressure would enhance interpretation of research findings, assist in substantiating manufacturers' claims of pressures exerted, and provide a greater understanding of garment pressure, which has the potential to be highly variable between individuals. Interface pressure measurement would also enhance future research undertaken into compression, enabling the investigation of optimal pressure gradients required for sports compression garments to improve recovery.

If researchers are to report interface pressure measurements, a valid and reliable pressure monitoring device should be used, alongside a standardised testing protocol. Several different systems have previously been assessed[19], with the Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia) reported to be valid and reliable[18-20]. Various methods have been utilised to assess the validity of the Kikuhime device. Flaud and colleagues[19] placed the sensor in a pressurised chamber, where the pressure of the chamber was measured using a different pressure sensor that had previously been calibrated with a water column. The authors concluded that the device had an overall error of 4.3%. Van den Kerckhove and colleagues[20] connected the Kikuhime pressure sensor to a water column to compare pressure readings, reporting a linear relationship between the two measures up to a pressure of 30mmHg. Experimental trials undertaken by Partsch and Mosti[18] involved the sensor being placed between a rigid cylinder and an inflatable blood pressure cuff connected to a mercury manometer, as well as an *in-situ* measurement involving a human limb for the same procedure. The authors declared the device to be accurate, with a coefficient of variation (CV) of 4.17% within the tested range on the human limb. However, their results showed a high pressure variation for pressures below 30mmHg.

Two of the aforementioned papers also investigated the Kikuhime device's reliability. Flaud and colleagues[19] noted the importance of re-creating *in-situ* measurement as closely as possible for these measurements, but chose not to use a human limb due to the high likelihood of its variability influencing results. Rather, a cylindrical model leg with a constant curvature was used to gather data on repeated measures. Flaud and colleagues[19] reported favourably on the repeatability of the device, with the standard deviation (SD) of repeated measures less than 0.6mmHg and the CV between 2-3.5%. Although there are difficulties in using a human limb to assess reliability, it is critical that *in-situ* measurements be taken so that reliability of the device can be tested in a practical setting, as this is the intended use of the sensor.

Studies involving the Kikuhime device are yet to quantify the intra-tester and inter-tester reliability of the instrument when measuring *in-situ* interface pressure of compression garments on uninjured skin on the lower limb. This information is of particular relevance to further studies investigating the use of lower limb sports compression garments, as previous validity and reliability of the Kikuhime device relates to conditions of burns, venous ulcers or other medical complications. The aims of the current study were two-fold: to determine the validity of the Kikuhime device by comparing it directly to a "gold standard" across a range of pressures, and to determine the inter- and intra-tester reliability when using the Kikuhime device to measure sport compression garments over six landmarks on an athlete.

Methods

The Kikuhime pressure monitoring device:

The Kikuhime pressure monitoring device consists of a pressure transducer connected to a detachable 70cm length of silicon tubing, which attaches to an oval-shaped polyurethane sensor (30mm x 38mm). Inside the sensor is a 3mm-thick sheet of polyurethane foam. The pressure exerted on the balloon is directly transmitted to the transducer and continuously displayed in real time in 1mmHg increments.

The device was tested in a temperature-controlled laboratory (22.4 ± 0.3°C). Two methods were used to evaluate the performance of the sensor, first for validity, and then for intra-tester and inter-tester reliability *in-situ*.

Water column (gold standard measure used for validity):

The pressure sensor was placed at the bottom of a 160cm-tall clear cylindrical container. A steel measuring tape was attached to the outside of the cylinder, before it was filled to predetermined levels with de-ionised water. The water's temperature was measured with a TM50 thermometer (Temp-Seeker, Florida, USA) so as to determine the density of the water. The water's density dictated the water depths selected so as to apply interface pressures from

5-100mmHg to the sensor, in 5mmHg increments. The depth of water required to produce these pressures was calculated using the equation,

$$a \text{ mmHg} = b \text{ mmH}_2\text{O x } [7.35559135 \text{ x } 10^{-2}]$$ [82]

Depth measurements were taken as the distance between the lowest point of the water's meniscus and the centre of the pressure sensor. Repeat measurements for three separate detachable sensors were recorded at each depth/pressure. At the time of testing, all sensors were new and unused.

Measurements in-situ (intra- and inter-tester reliability)

A well-trained male endurance runner (height 1.86 m, body mass 71.0 kg, sum of 7 skinfolds 35.1 mm) signed an informed consent document approved by the Australian Institute of Sport and University of Tasmania Ethics Committees before being fitted with sports compression leggings (2XU compression leg sleeves, Victoria, Australia). The pressure sensor was positioned on the lower right leg prior to the leggings being worked up the legs so that the lower edge of the cuff on the ankle of the garment aligned with the distal border of the medial malleolus. The sensor was then aligned to measure pressure at six different landmarks along the leg.

The landmarks were positioned 5cm proximal to the distal border of the medial malleolus (A), 5cm proximal to A (B), on the medial aspect of the maximal calf girth (C), on the anterior aspect of the thigh 10cm below landmark E (D), the mid-point between the inguinal crease and the superior-posterior border of the patella (E) and 5cm proximal to landmark E (F) (Figure 2.1). Landmarks were chosen based on previous research investigating sports compression garments[83,84] and the commonly used European Standards for testing compression in medical hosiery[23,85,86].

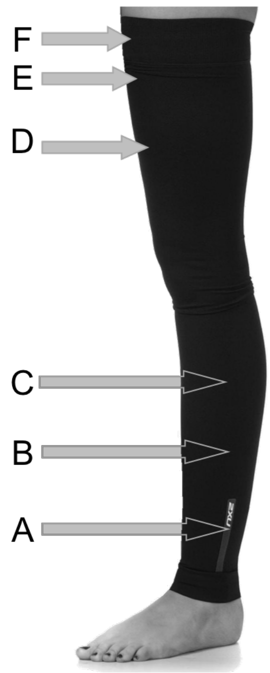

Figure 2.1 Landmarks A (5cm proximal to the distal border of the medial malleolus), B (5cm proximal to A), C (medial aspect of the maximum calf girth), D (anterior aspect of the thigh, 10cm below E), E (the mid-point between the inguinal crease and the superior- posterior border of the patella) and F (5cm proximal to E), where interface pressure measurements were taken.

The pressure exerted at each of these landmarks was measured while the participant was standing with their feet shoulder-width apart and their weight evenly distributed. Following the completion of these measurements, the leggings were removed and the procedure repeated by another researcher. This process was carried out five times by each researcher (ten measurements per site). The same pair of leggings was used throughout the testing protocol following the results of pilot testing in our laboratory that reported the maintenance of interface pressure for at least fifteen wears from new (unpublished observations). Landmarks were palpated by the experimenter and marked with a pen. Marks were removed with an alcohol swab between trials so as to further reduce the possibility of experimenter bias. A third party was responsible for reading and recording measurements on the Kikuhime device.

Data analysis

An intra-class correlation (ICC) was used to analyse the validity of the Kikuhime device, by comparing sensor readings to reference values.

Accuracy was evaluated using the global error calculation [87],

Global error = Average $\left|\frac{P - P_{ref}}{P_{ref}}\right|$

where P is the measured pressure and P_{ref} is the reference pressure.

Systematic errors were analysed by calculating the bias, using the Bland and Altman approach [88].

$$\text{Bias} = d \pm 2s$$

where d is the mean and s is the standard deviation of $P - P_{ref}$

Intra- and inter-tester reliability were assessed via the calculation of typical error of measurement (TEM) [89]. TEM was calculated as:

$$\text{TEM} = \text{SD} \times \sqrt{2}$$

where SD is the standard deviation of measures at each site. CV was calculated from the TEM so that it could be expressed as a percentage change, removing the tendency for larger values to report a more substantial TEM[90]. These analyses were performed using Microsoft Excel software (Microsoft Office Excel 2007, Redmond, Washington, USA). Data are presented as mean ± SD.

Results

Validity of the Kikuhime device

Results from the validity analysis of the Kikuhime device are presented in Table 2.1. All three sensors tested exhibited a very strong correlation with the reference value (mean ICC=0.996). Global error was calculated to have a mean value of 2.97% across the three sensors. This consisted of a mean bias (systematic error) of 2.28% and a random error of 0.69%.

Table 2.1 Intra-class correlation, global error, bias and coefficient of variation for the three Kikuhime sensors.

	Intra-class Correlation	Global Error (%)	Bias	Random error (%)	Coefficient of Variation (%)
Mean	0.996 ± 0.002	2.97 ± 2.67	2.28 ± 2.44	0.69 ± 0.23	1.11 ± 0.15

Figure 2.2 displays the differences between the reference pressure values and those displayed by the Kikuhime device. Perfect accuracy was displayed by all sensors up to a pressure of 35mmHg.

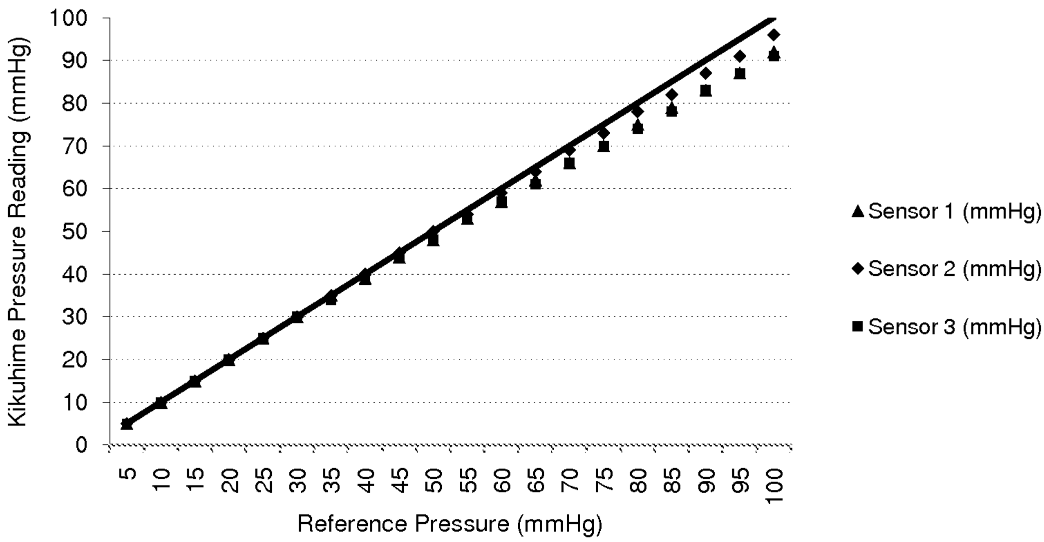

Figure 2.2 Comparison of the reference pressure with the measurements recorded by the Kikuhime device (reference pressure denoted by black line).

Measurements in-situ of intra-tester reliability

Table 2.2 exhibits the TEM and CV for both the intra- and inter-tester reliability of the Kikuhime device. The mean TEM for the five sets of recordings across the six landmarks used for intra-tester reliability was 1.3 ± 0.9mmHg, with a CV of 4.9 ± 2.4%.

Measurements in-situ of inter-tester reliability

Inter-tester analysis across the six sites resulted in a mean TEM of 1.8 ± 0.9 and mean CV of 7.4 ± 5.4% (Table 2.2).

Table 2.2 Mean pressure, Typical Error of Measurement (TEM) and Coefficient of Variation (CV) calculated from the intra-tester and inter-tester reliability analysis.

		Site A	Site B	Site C	Site D	Site E	Site F	Mean
Mean Pressure (mmHg)		22.2 ± 2.7	29.8 ± 2.3	32.4 ± 3.7	17.6 ± 1.9	22.9 ± 0.9	24.6 ± 1.1	
Intra-tester	Mean TEM	1.1 ± 1.5	1.1 ± 1.6	3.0 ± 4.2	0.6 ± 0.9	0.9 ± 1.3	0.9 ± 1.3	1.3 ± 0.9
	Mean CV	4.5 ± 6.4	3.7 ± 5.3	9.8 ± 14.1	3.6 ± 5.1	4.2 ± 6.0	3.8 ± 5.5	4.9 ± 2.4
Inter-tester	Mean TEM	2.7 ± 3.8	2.6 ± 3.6	2.3 ± 3.3	1.9 ± 2.7	0.8 ± 1.1	0.6 ± 0.8	1.8 ± 0.9
	Mean CV	13.3 ± 19.3	8.9 ± 12.8	7.7 ± 11.0	12.4 ± 18.0	1.0 ± 4.8	1.0 ± 3.4	7.4 ± 5.4

TEM=typical error of measurement (mmHg), CV=coefficient of variation (%)

Discussion

This is the first study to assess the reliability and validity of the Kikuhime device *in-situ* on an athlete wearing sports compression garments. The results from the current study show the Kikuhime to be a valid and reliable device that can be used to measure pressure gradients of compression garments on uninjured skin. The Kikuhime device exhibited a very strong intra-class correlation when compared to a reference value (ICC=0.996), and displayed a low TEM when analysed for intra- and inter-tester reliability *in-situ* (TEM=1.3 ± 0.9mmHg and 1.8 ± 0.9mmHg, respectively), as would be required to investigate compression clothing.

Previous studies have assessed the Kikuhime's validity with favourable outcomes[18-20]. However, the studies have each included possible sources of error by comparing the Kikuhime device's measurements to other devices or non-validated techniques. This study is the first to assess the Kikuhime device by immersing the sensor under a column of water, which is thought to provide a "gold standard" method of validation. The strong ICC (0.996) supports the results by previous investigations that have demonstrated the Kikuhime to be a valid instrument[18,19]. The current study adds to the literature by comparing the Kikuhime device to a large range of pressures, while most other papers have limited investigated pressures to a maximum of 30mmHg[19,20].

Investigating beyond these bounds allowed the device's limitations to be detailed more clearly. The results of the current study are in stark contrast to those produced by Partsch and Mosti[18], which detailed the largest differential between the reference value and the Kikuhime device at pressures below 30mmHg, whereas this was the most accurate range for the current investigation. A plausible explanation for this difference would be that the reference value (blood pressure cuff) used in Partsch and Mosti's[18] experiment applied an uneven pressure on the Kikuhime sensor surface due to deformation of the cuff, particularly at lower pressures. The disagreement may also explain the difference in CV between the two studies, with the current study producing a lower CV of 1.11%, while Partsch and Mosti[18] reported a CV of 4.17%. Similar comparisons are apparent when the global error of the current findings are assessed against that reported by Flaud and colleagues[19] (global error=4.30%), with a lower value reported in the current study (global error=2.97%). Again, the value of using a direct assessment method must be recognised in this situation as it assists in reducing possible sources of error. Further to these results, Flaud and colleagues[19] reported a bias similar to that of the present study (-1.4 ± 2.0), suggesting that random errors contributed to the greater global error reported by their study. It must be noted that the current study assessed the Kikuhime's validity under constant environmental conditions (22.4 ± 0.3°C), and therefore results can only be interpreted within these parameters, and not extrapolated to encompass differing ambient temperature conditions. The study did not assess the Kikuhime device's sensitivity to mechanical hysteresis either, and this may influence the accuracy of repeated measurements[80].

The intra-tester TEM of 1.3 (± 0.9) was particularly low, especially considering the 1mmHg resolution of the Kikuhime device and the wide range of pressure measurements exhibited in Table 2.2. TEM was regarded as a more pertinent measure than CV for the Kikuhime device, as CV was skewed by this low resolution. Similar results were reported by Van den Kerckhove and colleagues[20], who assessed intra-tester reliability by means of repeated measures on a plastic cylinder and reported a TEM of 1.46mmHg. These values suggest strong intra-tester reliability when trained personnel use the Kikuhime device according to a specific protocol.

Inter-tester reliability in the current study returned a higher TEM and CV than intra-tester reliability (1.3 ± 0.9mmHg and 4.9 ± 2.4%, as opposed to 1.8 ± 0.9mmHg and 7.4 ± 5.4%, respectively). Values were similar to those reported by Van den Kerckhove and colleagues[20] (TEM=1.89mmHg). The sensitivity of the device to 1mmHg further strengthens the credibility of these values representing a reliable instrument.

In conclusion, the Kikuhime pressure monitoring device is a valid and reliable tool, exhibiting a global error of just 2.97% and intra- and inter-tester reliability TEM of 1.3±0.9mmHg and 1.8 ± 0.9mmHg, respectively, when assessed on an athlete assuming a standing posture. The instrument proved to be extremely accurate to 35mmHg. With the majority of interface pressure measurements falling within this range, the Kikuhime is a suitable instrument for use in research studies involving sports compression garments *in-situ*. It is important to acknowledge that the Kikuhime device may be sensitive to temperature and hysteresis, and therefore the findings of this study are limited to the environmental conditions under which the sensors were assessed.

Acknowledgments

The authors of this paper would like to acknowledge 2XU Australia for supplying the compression garments used for testing.

Chapter 3:

Pressure gradient differences between medical grade and sports compression socks

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Running Title: Medical and sport compression

Total word count: 1 736

Abstract word count: 253

Number of Tables: 1

Number of Figures: 2

Manuscript submitted to *Sports Engineering*

Rationale

The premise behind the use of compression garments by athletes originates from the evidence of their capacity to induce physiological changes in clinical populations. However, it remains to be seen whether sports compression garments exhibit similar physical characteristics to those adopted in a medical setting. This study assessed medical grade and sports compression socks using the previously validated Kikuhime pressure monitoring device (Chapter 2) to highlight whether there was any difference in interface pressure application.

Abstract

Purpose: The use of compression garments designed for athletes has become increasingly popular following the long-standing use of similar garments in the clinical setting. However, it remains to be seen whether the two different garments (sports and medical) exhibit the same physical properties. This study aimed to quantify any differences that may be apparent in the interface pressure applied by sports and medical compression garments.

Methods: Sixty (30 male, 30 female) national representative athletes were fitted with both medical grade and sports compression socks in a counterbalanced order. Interface pressure was assessed using a Kikuhime pressure monitor at three different landmarks on the lower leg to better understand absolute pressure application and pressure gradient.

Results: Medical grade compression socks exerted a *small*, yet significantly higher mean pressure across the three landmarks (28.8 ± 4.4mmHg) than sports compression socks (26.3 ± 4.0mmHg, $p<0.001$, $d=0.57$). However, it is unknown whether this pressure differential is great enough to result in a meaningful impact on physiological responses, and thus potentially beneficial outcomes from wearing the garments. Both garment types exhibited progressively graduated pressure profiles, where pressure is highest at the proximal end of the limb and lowest at the distal end. This is contrary to the commonly accepted graduation of pressure required for blood flow augmentation.

Conclusion: These findings highlight the possible differences between compression garments that practitioners should be aware of when recommending such attire to athletes. The disparity present may affect the likelihood of similarly beneficial effects elicited by both garment types, however further investigation into the smallest meaningful difference in pressure application is required before such claims can be founded.

Keywords: interface pressure, compression garments, sports performance, exercise recovery

Introduction

Compression garments are a popular tool for enhancing exercise performance and recovery[91]. The use of compression socks initially stems from their application in a medical setting, where socks and stockings have been in use for over 50 years[92]. The market for sports compression garments is growing rapidly[93] under the premise that compression socks assist in increasing blood flow and reducing oedema[5]. Compression socks are particularly popular, with our recent survey of elite Australian athletes reporting them to be the second most commonly used compression garment, worn by over 65% of respondents[4].

Medical grade compression garments have been shown to improve circulation, lymphatic flow and venous return in clinical populations[9,94,95]. Their benefits in a clinical setting also extend to the reduction of swelling and oedema[10,96]. It is proposed that these outcomes would benefit athletes by improving removal of waste products built up during exercise, supplying fatigued muscles with oxygen-rich blood, and reducing inflammation and soreness post-exercise[26,91,97].

Research into the efficacy of wearing compression garments in a sporting setting has produced equivocal results, with some investigators reporting improvements in both performance[62] and recovery[2,14], while others have displayed no differences in performance-based outcomes[67,91]. These mixed findings have been the foundation of scepticism in some recent reviews on the capacity for the beneficial effects illustrated in clinical settings to be transferred to athletes wearing sports compression garments[5]. Hill and colleagues[17] have provided further weight to this uncertainty, reporting that medical grade compression tights were more effective than sports compression garments in muscle strength recovery following a bout of eccentric resistance training.

The properties of the garments must first be assessed before attempting to infer possible physiological mechanisms evoked by compression garments within the realm of sporting performance. To date, there have been no investigations into whether sports compression garments replicate similar pressure profiles to medical grade compression garments. Additionally, optimal pressure application and pressure gradient are also yet to be agreed upon. Liu and colleagues[22] suggested that pressure ≥18mmHg was required to instigate changes in haemodynamics, while Bochmann and colleagues[39] recommended pressure ≥20mmHg to increase limb blood flow, but this is yet to be extensively explored in an athletic population.

The aim of this study was to compare the interface pressures applied by sports and medical grade knee-length compression socks, and to investigate any possible pressure gradients created by these garments.

Methods

Participants

Sixty (n=30 males, 30 females) national representative athletes from a wide variety of sports participated in the current study (Table 3.1). All participants were informed of the study protocol before signing an informed consent document approved by the Australian Institute of Sport and the Tasmanian Research Ethics Committees.

Table 3.1 Cross-section of the athlete cohort recruited for the investigation.

	Male	**Female**	**TOTAL**
Aerial Skiing	1	3	4
Boxing	5		5
Endurance sports	5	3	8
Football codes	5	1	6
Gymnastics		8	8
Netball		15	15
Volleyball	14		14
TOTAL	30	30	60

Compression Garments

Sports compression socks (2XU, Victoria, Australia) and medical grade compression socks (Venosan, North Ryde, NSW) were used in the current study. The sports compression socks comprised of 72% nylon (140 denier) and 28% Lycra® elastane (360 denier), while the medical grade compression socks consisted of 71% Tactel® polyamide and 29% Lycra® elastane (480 denier). Both were graded with a level II compression rating, defined by a pressure range of 23-32mmHg (German standard, RAL-GZ 387:2000[98]).

The socks were applied to cover the entire area of the lower limb distal to the tibial tuberosity, and were fitted to each athlete according to manufacturer's sizing guidelines. The sizing guidelines were based on the athlete's calf girth at three landmarks, and shoe size.

Design

Athletes reported to our laboratory for a single testing session. The testing session involved the athletes trying on two different compression socks in a counterbalanced order.

Experimental Protocol

Socks were worked up the athlete's lower leg, before athletes were instructed to stand with their feet shoulder-width apart with their weight evenly distributed. A Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia), previously determined to be a valid and reliable measurement tool in our laboratory with a coefficient of variation ranging from 4.9%[99], was used to measure interface pressure.

The pressure sensor was inserted on the medial aspect of the lower leg between the skin and the sock to measure interface pressure. Once in this position, the distal border of the medial malleolus was palpated to use as a reference point for the three measurement sites used in this study. Pressure measurements were taken at 5cm proximal to the distal border of medial malleolus (A), 5cm proximal to A (B), and on the medial aspect of the maximum calf girth (C) (Figure 3.1).

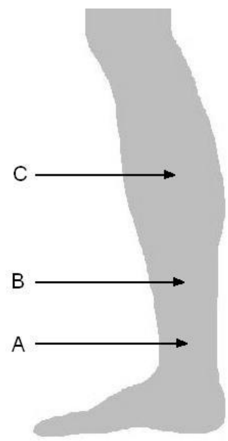

Figure 3.1 Landmarks A (5cm proximal to the distal border of the medial malleolus), B (5cm proximal to A) and C (medial aspect of the maximum calf girth), where pressure measurements were recorded.

This process was repeated so that six measurements were taken for each participant; three while wearing a sports compression sock and three when a medical compression sock was worn.

Statistical Analysis

Skewness and kurtosis, as well as visual assessments of histograms, were used to ensure normal data distribution before statistical analyses were completed. A paired-samples t-test was used to determine whether there was a difference in average pressure application apparent between the two garments. One-way ANOVAs were used to assess differences between each measured landmark for each type of garment, with Bonferroni post-hoc analyses used to determine where specific differences occurred. Significance was set at $p \leq 0.05$.

Cohen's effect sizes (*d*) were also calculated to determine practical differences between garments and landmarks. These were interpreted using the following criteria: <0.2, trivial; 0.2-0.6, small; 0.6-1.2, moderate; 1.2-2.0, large; >2.0, very large[100]. The effect was deemed "clear" if 90% confidence limits of the two conditions did not overlap. Data are presented as mean ± standard deviation.

Results

Medical grade compression socks exerted a significantly higher mean pressure (28.8 ± 4.4mmHg) than sports compression socks (26.3 ± 4.0mmHg, $p<0.001$). The difference between garments was considered to be *small* and clear (d=0.57). Medical grade compression socks had a *moderate* clear effect on interface pressure at both Landmarks A (p=<0.001, d=0.77) and B (p=<0.001, d=0.65), with significantly higher pressure applied than sports compression socks (Figure 3.2). No difference was apparent between garments at Landmark C (p=0.39, d = 0.03).

Interface pressure differed significantly between landmarks for medical grade compression socks ($p<0.001$, Figure 3.2). Post-hoc analyses revealed the pressure exerted at landmark A

(25.0 ± 5.6mmHg) to be significantly lower than at landmark B, with a *moderate* effect size (29.5 ± 5.2mmHg, p<0.001, *d*=0.87). There was no significant difference between pressure at landmark B and landmark C (31.7 ± 6.1mmHg, p=0.10, *d*=0.38). A *moderate* significant difference was apparent between landmarks A and C (p<0.001, *d*=1.11). These differences reflect the foundations of a reverse, or progressive, pressure gradient, characterised by highest pressure at the proximal end of the limb and lowest at the distal end [33].

Sports compression garments also varied in interface pressure application between landmarks (p<0.001). Pressure at landmark A (21.0 ± 4.7mmHg) was significantly lower than at landmark B (25.8 ± 6.1mmHg, p<0.001). This difference was considered to have a *moderate* effect size (*d*=0.79). Similarly, interface pressure at landmark B was significantly lower than at landmark C (*moderate* effect size, 32.0 ± 6.1mmHg, p<0.001, *d*=1.02). A *large* significant difference was apparent between landmarks A and C (p<0.001, *d*=1.80). These differences also revealed a progressively graduated pressure profile.

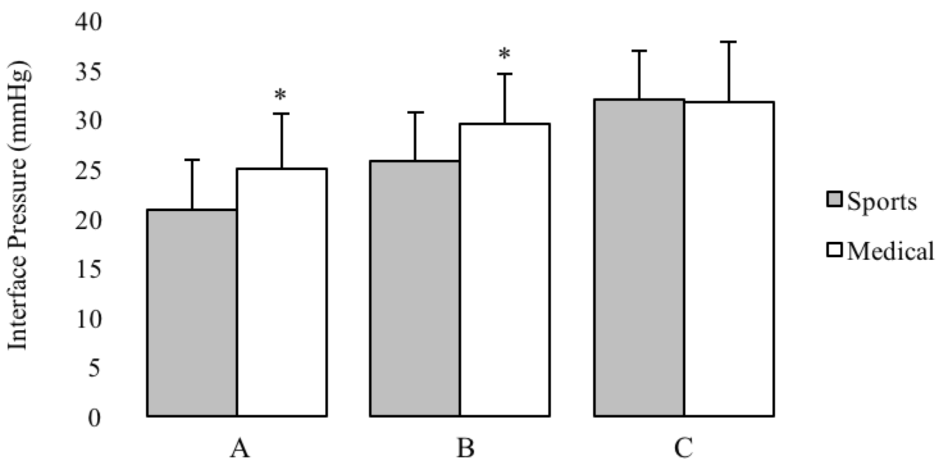

Figure 3.2 Mean pressure (+ standard deviation) applied by sports and medical grade compression garments at three landmarks on the lower leg. See Figure 3.1 for landmark definitions.
*represents significant difference from sports compression socks, p<0.05.

Discussion

Results from the current study suggest that sports compression socks and medical grade compression socks exhibit *small*, but statistically significant differences in pressure profiles when worn by athletes. Although both garments used in the investigation were rated identically by an internationally recognised pressure standard[98], the medical grade socks applied higher interface pressure. The rapidly expanding market for sports compression garments[71] makes this finding pertinent as it questions whether the beneficial physiological changes experienced when using medical grade compression socks in a clinical setting can be transferred to athletic populations using sports compression socks.

Although the average pressure applied by medical grade compression socks was significantly higher than sports compression socks, the optimal pressure synonymous with increases in blood flow is yet to be determined. Liu and colleagues[22] assessed the capacity of compression stockings with varying levels of pressure to alter venous blood flow. Results suggested that pressure ≥18mmHg was more effective than pressure ≤12mmHg in increasing venous flow. A similar pressure range (≥20mmHg) has also been reported as most effective in increasing forearm blood flow[39]. Both garments in the present study applied far greater pressure than the suggested minimum standards[22,39], so it is unknown whether the medical compression socks could indeed infer superior benefits to the sports compression socks or that both types would be fit for purpose.

Traditional statistical analyses performed in this investigation found a significant difference in pressure application between garments; however, the attempt to apply practical statistical analysis by calculating Cohen's *d* effect sizes, begins to question whether this statistically significant difference is indeed meaningful. As previously discussed, Liu and colleagues[22] were able to differentiate between garments that exhibited a difference in applied pressure of ≥6mmHg. The difference in the present study (2.5 ± 4.6mmHg) could likely be considered negligible given that debate continues in the literature as to whether sports compression garments have any true physiological impact on athletes' blood flow parameters[3,37,49].

The optimal pressure gradient applied by compression garments has long been understood as graduated in nature, with the highest pressure at the distal end of the limb and the lowest pressure at the proximal end[101]. However, more recent research has revealed that graduated compression is not necessarily always present in sports compression garments[102], and may not even be the most effective method of augmenting venous return, with Mosti and colleagues[101] suggesting the concept of progressive or reverse graduation may yield greater benefits. Of interest, both the medical grade and sports compression socks investigated in the present study were found to exhibit this progressively graduated pressure profile. As previously suggested, this may provide greater benefits to the user, under the premise that higher pressure is being applied to the large muscle belly, in this case, the calf[101].

This study illustrated that the medical grade and sports compression socks investigated differed in pressure application, and that both exhibited progressive pressure gradients, when fitted to athletes. These findings highlight the potential for different physiological outcomes to be facilitated by sports compression socks compared to those brought about by medical compression socks. However, further research should seek to quantify the pressure application required to elicit physiological changes in athletes so as to better understand whether this difference is in fact meaningful.

Chapter 4:

Confounding compression: The effects of posture, sizing and garment type on measured interface pressure in sports compression clothing

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Running title: Confounding variables in compression clothing

Total word count: 2 875

Abstract word count: 180

Number of Tables: 0

Number of Figures: 4

This chapter has been published as:

Brophy-Williams, N., Driller, M. W., Shing, C. M., Fell, J. W. & Halson, S. L., Confounding compression: The effects of posture, sizing and garment type on measured interface pressure in sports compression clothing, *Journal of Sports Sciences*, 2015, 33(13):1403-10.

Thomson Reuters Impact Factor (2017): 2.54

19 citations as at February 2018

Rationale

This study was intended to improve our understanding of the various factors that may affect the interface pressure applied by sports compression garments. The previous study displayed that they likely exhibit similar pressure profiles to medical grade compression garments (Chapter 3), but it was hypothesised that different garment types and sizes, and the posture assumed by athletes during measurement, would all affect pressure application. Participants were assessed wearing under-sized, manufacturer recommended-size and over-sized sports compression tights and sports compression leggings in lying, seated and standing postures to comprehend the impacts these variables had on pressure profiles as various postures are replicable of the positions adopted by athletes during and post-exercise. The Kikuhime pressure monitor (Chapter 2) was used to measure pressure at six landmarks across the lower limb under these conditions.

Abstract

The purpose of this investigation was to measure the interface pressure exerted by lower body sports compression garments, in order to assess the effect of garment type, size and posture in athletes. Twelve national level boxers were fitted with sports compression garments (tights and leggings), each in three different sizes (under-sized, recommended size and over-sized). Interface pressure was assessed across six landmarks on the lower limb (ranging from medial malleolus to upper thigh) as athletes assumed sitting, standing and supine postures. Sports compression leggings exerted a significantly higher mean pressure than sports compression tights ($p<0.001$). Over-sized tights applied significantly less pressure than manufacturer-recommended size or undersized tights ($p<0.001$), yet no significant differences were apparent between different sized leggings. Standing posture resulted in significantly higher mean pressure application than a seated posture for both tights and leggings ($p<0.001$ and $p=0.002$, respectively). Pressure was different across landmarks, with analyses revealing a pressure profile that was neither strictly graduated nor progressive in nature. The pressure applied by sports compression garments is significantly affected by garment type, size, and posture assumed by the wearer.

Keywords: Compression garments; sports performance; exercise recovery, graduated compression

Introduction

Compression garments are becoming commonly used in a sporting setting with the theory of enhancing both performance and recovery[1]. Many of the benefits associated with the use of compression garments are attributed to an increase in venous[9] and arterial[39] blood flow. It is reported that the optimal method of applying compression to increase blood flow, is to do so in a graduated fashion (i.e. highest pressure exerted at the distal end of the limb decreasing to a lower pressure exerted at the proximal end of the limb)[39,103]. Graduated compression has been used in the medical industry for many years to prevent lymphoedema and manage wounds, scars and venous leg ulcers[104]. Compression garments are believed to assist in relieving these ailments by optimising circulation, giving the premise for use in the sporting industry[43]. Although there has been research in a clinical setting as to whether the most effective compression design is graduated, uniform or progressive (where pressure is greatest at the proximal end of the limb, decreasing to a lower pressure at the distal end of the limb) in nature[101,103], there are yet to be any such investigations involving healthy participants and sports compression garments.

The existing research investigating the efficacy of sports compression garments for both performance and recovery has produced equivocal results[5]. Unfortunately, the vast majority of research papers in this area have not measured interface pressure applied by the garments being investigated[14,28,29]. A plausible explanation for studies concluding compression to be of no benefit is that they may not have applied adequate interface pressure to induce measurable changes. Studies that have reported interface pressure measurements have often assessed only two sites, commonly the calf and the mid-thigh which, in isolation, frequently reflect the manifestation of graduated compression[32,35]. However, research is yet to determine whether sports compression garments exhibit true graduated compression across the length of the limb, or even whether this is necessarily the best method to elicit any optimal change in blood flow and/or performance in an athletic population[26].

Regardless of pressure graduation, it has been recognised that different postures and foot positions during the application of compression elicit variations in interface pressure[105]. Wertheim and colleagues[105] assessed the effect that limb movement has on interface pressure applied by compression bandages; however, the authors expressed the need to further investigate interface pressure in various postures. Aryal and colleagues[33] also recognised this void in the literature, and reported significant changes in interface pressure applied by below-knee medical grade compression stockings for landmarks close to the mid-calf with the alteration of posture. The authors attributed these changes to the contraction of the posterior calf muscles upon standing, the effect of venous pooling, or both. A range of postures are assumed by athletes when wearing sports compression garments for recovery purposes, from standing/walking, to sitting at rest and supine when asleep. Similar to medical grade compression garments, it is likely that the pressure exerted by sports compression garments is affected by posture, although these differences are yet to be quantified in the literature.

The interface pressure exerted by different sized garments is another area that is yet to be investigated in great detail. Compression tights fitted in accordance with manufacturer's guidelines have been compared to garments one size smaller than recommended during an endurance running effort, with no differences found in exercise performance or physiological measures [32]. Interface pressure was measured at two sites for both sizes, with results suggesting that under-sized garments exerted more pressure than recommended size garments; however, no statistical analysis was presented to justify this assessment. Ideally, a more complete pressure profile should be established so as to quantify differences between the garments assessed.

The aim of the current study was to determine the interface pressure applied to human limbs by various sizes of sports compression tights and sports compression leggings, while participants assumed different postures.

Methods

Participants donned six separate compression garments over the course of the testing session: three sets of tights and three pairs of leggings (under-sized, recommended size and over-sized). The undersized and oversized garments were one size smaller and one size larger, respectively, than the size recommended by the manufacturer's guidelines. Participants were assigned in a counter-balanced order to wear either tights or leggings first, and a counter-balanced Latin square model was used to determine the order of wear of the various sizes within those categories. Lying, standing and sitting postures were assessed in that order. Several studies have used wooden legs for ease of garment application and pressure measurement[19]; however, assessments involving a human limb have a higher ecological validity, as they take into account changes in posture and body composition.

Twelve male members of the national boxing team volunteered to participate in this study (age = 22.0 ± 4.5 years, weight = 78.6 ± 18.8 kg, medial calf skinfold = 6.3 ± 1.9 mm, mid-thigh skinfold = 10.0 ± 2.9 mm). The boxers represented the range of weight divisions, from light flyweight division (<50 kg) to super heavyweight division (>91 kg). The study was ethically approved by the university and institute's ethics committees and all participants provided informed, written consent.

The compression garments used were men's full-length tights, comprised of a combination of 70 & 105 denier LYCRA® fibre material (80% nylon, 20% elastane) and unisex full-length leggings, which comprised of 250 denier LYCRA® fibre material (80% nylon, 20% elastane). The garments ran from the distal border of the medial malleolus of the ankle to the superior border of the iliac crest (tights) or to the gluteal fold (leggings). Garments were fitted according to the manufacturer's guidelines using each participant's stature, body mass, mid-thigh girth and maximal calf girth, where appropriate.

The Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia) was used to evaluate the interface pressure exerted by each compression garment. The device consists of a pressure transducer connected to a length of silicon tubing, which attaches to an oval-shaped sensor that directly transmits pressure readings to the transducer, continuously displaying measurements in real time in 1 mmHg increments. It has been previously validated, and is a reliable and accurate tool for measuring compression garments (typical error of measurement = ± 1 mmHg)[99]. The Kikuhime device was positioned on the lower right leg before the tights or leggings were worked up the limb, so that the furthest point of the garment aligned with the distal border of the medial malleolus and there were no creases in the garment's fabric.

Interface pressures exerted by the garments were determined at six different landmarks across the lower limb. The landmarks were positioned 5cm proximal to the distal border of the medial malleolus (A), 5cm proximal to A (B), on the medial aspect of the maximal calf girth (C), on the anterior aspect of the thigh 10cm below landmark E (D), the mid-point between the inguinal crease and the superior-posterior border of the patella (E) and 5cm proximal to landmark E (F) (Figure 4.1). These landmarks were selected based on previous papers investigating sports compression garments[84,99,102] and guidelines stated by the commonly referenced[19,80,86] European Standards for testing compression in medical hosiery (European Committee for Standardization, 2009). The particular sites were chosen to reflect the pressures exerted on the muscle belly rather than that applied to the bony tissue wherever possible.

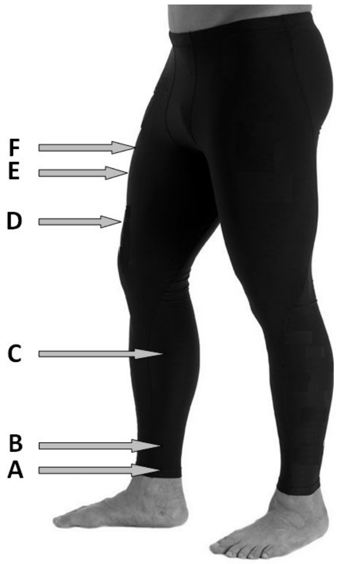

Figure 4.1 Landmarks A (5cm proximal to the distal border of the medial malleolus), B (5cm proximal to A), C (medial aspect of the maximal calf girth), D (anterior aspect of the thigh, 10cm below E), E (the mid-point between the inguinal crease and the superior-posterior border of the patella) and F (5cm proximal to E), where pressure measurements were recorded. Landmarks were adapted from the European Standards for testing compression in medical hosiery[23].

Each measurement was recorded while the participant was in a supine position, a standing position (feet shoulder-width apart, weight evenly distributed), and when seated (knees bent at a 90° angle, feet flat on floor), before the sensor was re-positioned at the subsequent landmark.

All data were first tested for normality using a Shapiro-Wilk normality test. All variables were normally distributed. Two-way ANOVAs were used to assess main effects of garment type by landmark, size by landmark and posture by landmark; with Bonferroni post-hoc analyses to determine where differences lay. Main effects of garment and landmark were assessed for recommended size leggings and tights in an upright posture. Significance was accepted at

$p<0.05$. Cohen's d was calculated from the difference between means divided by pooled standard deviation and the effect size was interpreted as small=0.2, moderate=0.5 and large=0.8[106]. Data are presented as mean and 95% confidence interval (CI) unless otherwise stated.

Results

There was a main effect of garment type and landmark and a significant interaction of garment by landmark on pressure (all $p<0.001$). Leggings exerted significantly greater pressure than tights (leggings mean pressure = 18.9 mmHg (CI 17.3 to 20.5 mmHg), tights mean pressure = 13.0 mmHg (CI 11.8 to 14.2 mmHg), d=0.99, Figure 4.2) when garments were fitted according to manufacturer's recommendations and athletes adopted a standing posture.

The highest pressure measurements while wearing recommended size tights in a standing posture were recorded at maximal calf girth (Landmark C, 20.5 mmHg (CI 18.6 to 22.4 mmHg)), where the pressure exerted was significantly greater than at the upper ankle (Landmark A, 9.4 mmHg (CI 7.2 to 11.6 mmHg), d=3.36, $p<0.001$). Pressure applied at the mid-thigh (Landmark E, 12.4 mmHg (CI 11.4 to 13.4 mmHg)) was significantly lower than the maximal calf girth (d=3.45, $p<0.001$). High pressure recordings were also observed at the maximal calf girth when leggings were worn under the same conditions (25.2 mmHg (CI 22.7 to 27.7 mmHg)). Pressure applied by leggings at the maximal calf girth was significantly higher than at the upper ankle (15.0 mmHg (CI 12.7 to 17.3 mmHg), d=2.68, $p<0.001$) and the mid-thigh (17.0 mmHg (CI 15.5 to 18.5 mmHg), d=2.60, $p<0.001$, Figure 4.2).

A main effect was apparent for both size and landmark (both $p<0.001$), but there was no significant interaction of size by landmark ($p=0.865$) when assessing pressure applied by compression tights while standing upright (Figure 4.3a). Post-hoc analyses revealed both under-sized tights (13.8 mmHg (CI 12.6 to 14.9 mmHg)) and recommended size tights (13.0 mmHg (CI 11.8 to 14.2 mmHg)) exerted significantly greater mean pressure than over-sized tights (10.4 mmHg (CI 9.4 to 11.4 mmHg), d=0.73 & 0.55, respectively, $p<0.001$ for both). No significant differences were apparent between under-sized and recommended size tights (d=0.16, $p=0.358$). For leggings, a main effect was also apparent for both size and landmark (both $p<0.001$), but there was no significant interaction of size by landmark ($p=0.724$, Figure 4.3b). Under-sized leggings (20.9 mmHg (CI 19.2 to 22.6 mmHg)) exerted significantly greater mean pressure than both recommended size leggings (18.9 mmHg (CI 17.3 to 20.5 mmHg), d=0.28, $p=0.006$) and over-sized leggings (17.8 mmHg (CI 16.2 to 19.3 mmHg), d=0.45, $p<0.001$). No significant differences were apparent between recommended size and over-sized leggings (d=0.17, $p=0.233$).

A main effect was apparent for posture ($p=0.014$) and landmark and there was a significant interaction of posture by landmark (both $p<0.001$) on pressure exerted by recommended size tights (Figure 4.4a). Adopting a supine posture (11.5 mmHg (CI 10.4 to 12.7 mmHg)) resulted in significantly lower pressure than standing (13.0 mmHg (CI 11.8 to 14.2 mmHg), d=0.30, $p=0.011$). No significant differences were apparent between sitting (12.3 mmHg (CI 11.4 to 13.1 mmHg)) and lying supine (d=0.18, $p=0.439$) or standing upright (d=0.18, $p=0.416$). A main effect was apparent for posture ($p=0.001$) and landmark ($p<0.001$) and a significant interaction of posture by landmark (both $p=0.002$) on pressure applied by recommended size leggings (Figure 4.4b). Adopting a supine posture (16.6 mmHg (CI 15.2 to 17.9 mmHg)) resulted in significantly lower pressure than standing (18.9 mmHg (CI 17.3 to 20.5 mmHg), d=0.37, $p<0.001$). No significant differences were apparent between sitting

(17.6 mmHg (CI 16.9 to 18.5 mmHg)) and lying supine (*d*=0.19, p=0.258) or standing upright (*d*=0.22, p=0.082).

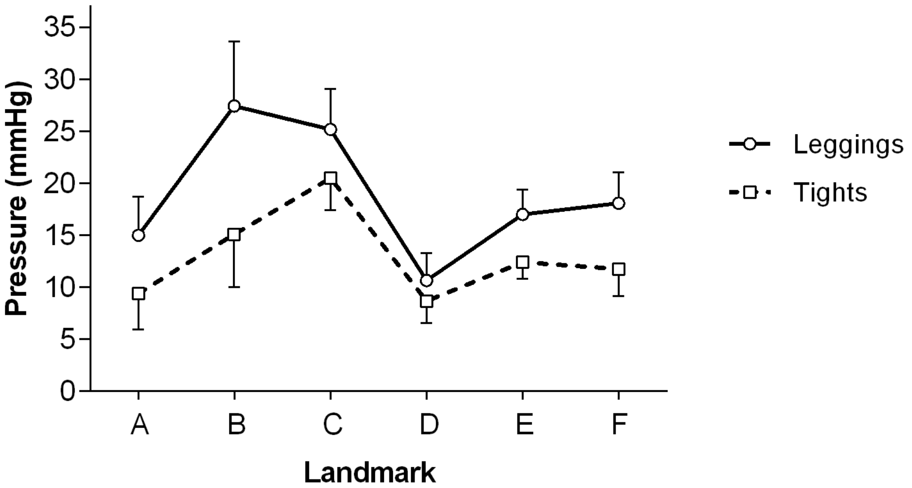

Figure 4.2 Mean interface pressure (± standard deviation) of recommended size sports compression leggings and sports compression tights when athletes adopted a standing posture. A significant main effect was apparent for both garment type and landmark (p<0.001).

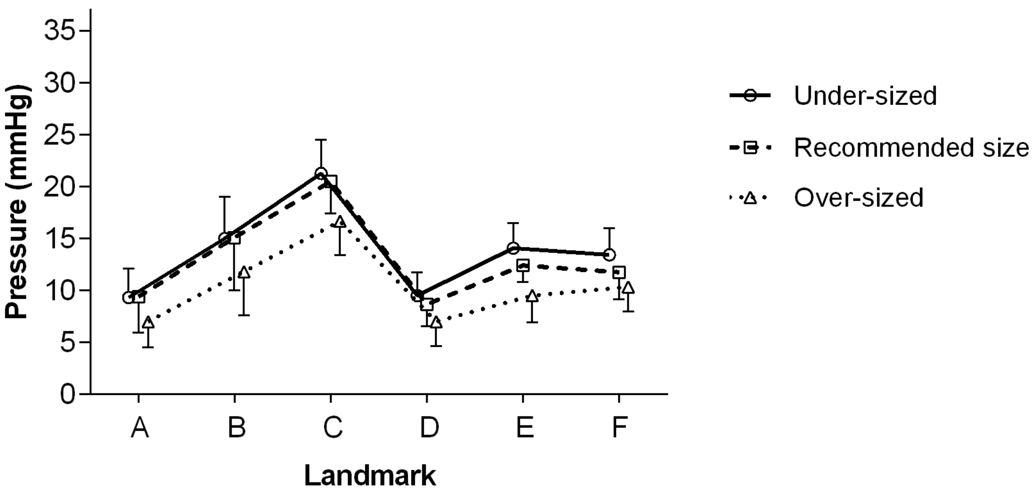

Figure 4.3a Mean interface pressure (± standard deviation) of under-sized, recommended size and over-sized compression tights when athletes adopted a standing posture. A significant main effect was apparent for garment size (p<0.001).

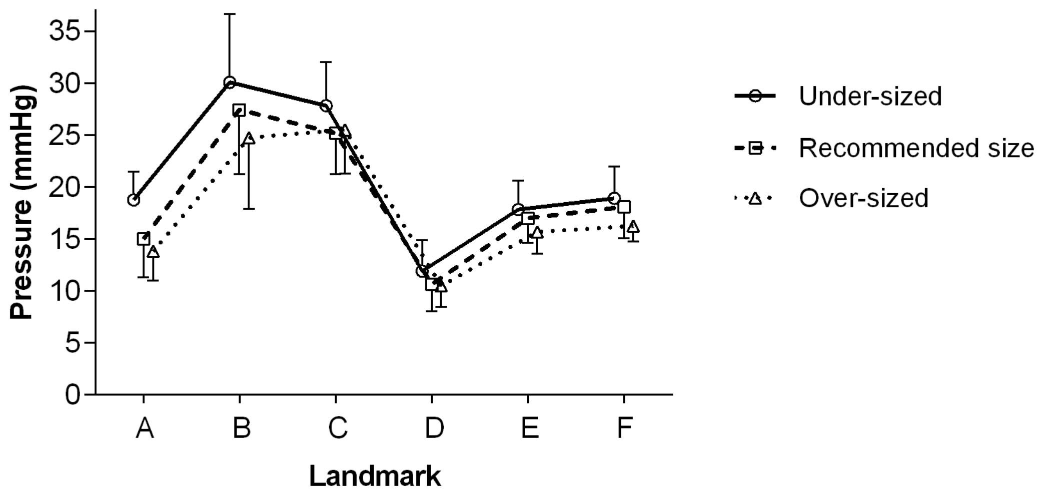

Figure 4.3 b Mean interface pressure (± standard deviation) of under-sized, recommended size and over-sized compression leggings when athletes adopted a standing posture. A significant main effect was apparent for garment size (p<0.001).

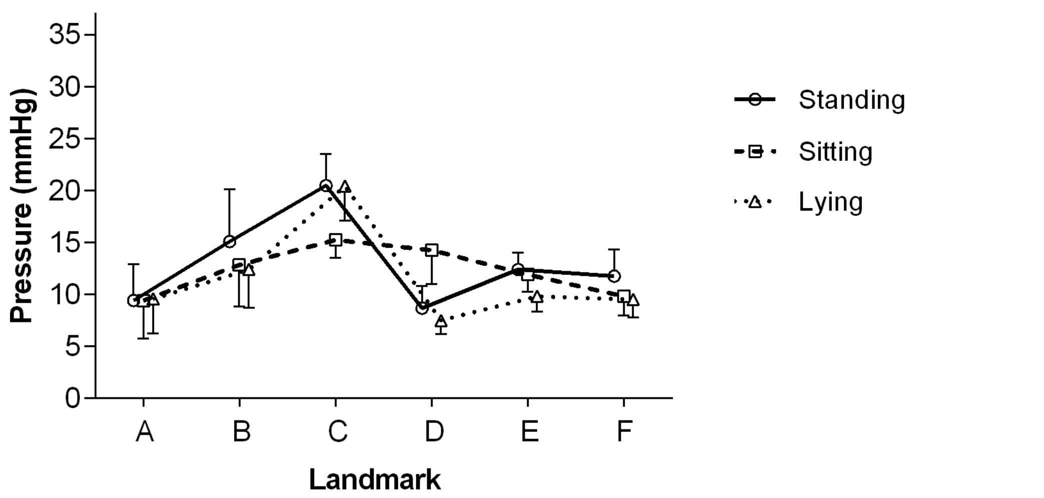

Figure 4.4a Mean interface pressure (± standard deviation) of recommended size sports compression tights worn in standing, sitting and supine postures. A significant main effect was apparent for posture (p<0.001).

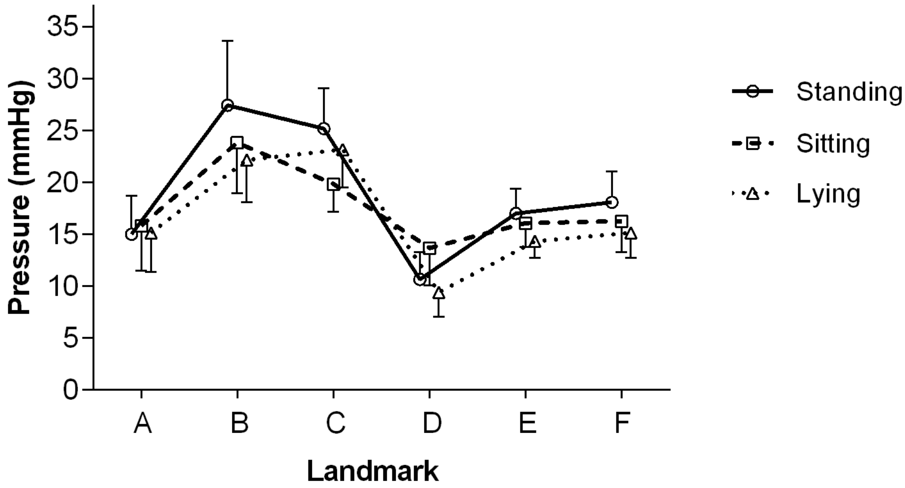

Figure 4.4b Mean interface pressure (± standard deviation) of recommended size sports compression leggings worn in standing, sitting and supine postures. A significant main effect was apparent for posture (p<0.001).

Discussion

The results of the current study indicate that there are significant differences in interface pressure gradients applied by sports compression garments. Compression leggings applied more pressure than compression tights, with smaller sizes and an upright posture also resulting in higher pressure application. The pressure at different landmarks on the lower limb also varied significantly. Studies evaluating potential physiological and performance benefits of sports compression garments should consider these differences in interface pressure across the limb that change in response to garment type, size and posture.

The physical dimensions of the sports compression leggings and sports compression tights were similar, so the greater pressure resulting from the leggings may be attributed to the higher fabric denier (70/105 denier and 250 denier for tights and leggings, respectively). Sperlich and colleagues[36] and Dascombe and colleagues[32] hypothesised a greater pressure, up to a certain degree, would be associated with greater haematological alterations, although the optimal pressure to induce the greatest increase in venous blood flow in an athletic population is yet to be determined. Lawrence & Kakkar[103] assessed various magnitudes of graduated compression application to the limbs of hospital patients and reported that applying pressure of 18 mmHg at the ankle, dissipating to 8mmHg at the calf (mean pressure = 12mmHg) to be most effective in increasing venous flow velocity when compared to higher and lower pressures. The application of a higher pressure (30mmHg at the ankle, dissipating to 12 mmHg at the calf) raised venous flow velocity to a similar extent as when 18 mmHg to 8 mmHg was applied, but simultaneously impaired absolute flow volume to the subcutaneous calf tissue, which may be attributed to a further reduction in cross-sectional vessel area[103]. Although sports compression tights and leggings exert different pressures, the optimal pressure to induce the greatest increase in venous blood flow is yet to be determined. Further investigations involving hemodynamic measurements in an athletic population wearing sports compression garments are required to determine potential mechanistic differences, if any, related to the different types of garment.

As would be expected, over-sized compression tights applied significantly less pressure to the athletes' limbs than recommended or under-sized tights. However, the lack of distinct difference between under-sized and recommended size tights highlights the need for research studies to standardise garments based on interface pressure measurements rather than purely manufacturers' recommendations, as many have done in the past[28,29,73]. Under-sized leggings applied significantly more pressure than recommended size leggings, yet no significant difference was apparent between pressure applied by recommended and over-sized leggings, further reinforcing the need for pressure measurement rather than reliance on manufacturers' sizing guidelines. One of the few studies to have investigated different sized sports compression garments involved the comparison of manufacturer-recommended size and under-sized sports compression tights worn during an endurance running performance[32]. While interface pressure was only measured at two landmarks on the lower limb, under-sized garments were reported to exert greater pressure than manufacturer-recommended size garments although this difference was not statistically quantified[32]. Findings of the current study suggest that under-sized garments exert significantly greater pressure than recommended and oversized garments.

The effect of changes in posture on interface pressure is particularly relevant for athletes who utilise sports compression garments for performance recovery while standing/walking, sitting and sleeping. The current study found that wearing the garments in a standing posture elicited significantly higher pressure than when athletes were supine. However, interface pressures when supine remain close to the supposedly optimal mean pressure of 12 mmHg, and well below levels shown to decrease venous calf flow[103]. Aryal and colleagues[33] reported changes in interface pressure applied by below-knee medical grade compression stockings when assuming different postures. The authors reported a pressure increase from sitting to standing, but changes were not statistically significant. Consequently, it appears that both sports and medical grade compression garments are affected by posture in a similar manner, with an upright posture resulting in increased interface pressure.

The vast majority of research papers to have investigated the application of sports compression garments have not measured the interface pressure levels applied by the garments[28,29,73], while those that have often assess pressure only at the calf and the mid-thigh[32,35]. The difference in pressure between these two sites may create the impression of graduated compression, as is the case for the calf and mid-thigh measurements for both tights and leggings in the current study. When pressures were determined at additional landmarks, it is apparent that the compression applied by the garments assessed was not of a graduated nature. Interface pressure at maximal calf girth was significantly higher than at the upper ankle for both tights and leggings. The difference in compression profiles revealed by the restricted and six-site profile reinforce the importance for further research in the field to report more comprehensive pressure profiles of garments. These assessments may lead to a better understanding of the effects of different compression architecture, be it graduated, uniform, progressive or a combination of these.

Conclusion

Different sports compression garments exert varying levels of compression, with the sports compression leggings assessed in the present study found to exert significantly more pressure than the sports compression tights. Similarly, posture and size had significant effects on interface pressure, with smaller sizes and a standing posture resulting in the highest pressure, while over-sized garments and athletes adopting a seated posture had the least pressure applied to their limbs by the compression garments. Interestingly, neither garment exhibited the widely reported concept of graduated compression when all six landmarks were collectively assessed. Reporting specific posture, garment type and pressure at specified landmarks will facilitate the interpretation of findings from research involving sports compression garments.

Chapter 5:

Comparison between the effects of knee- and thigh-length compression garments on limb volume and blood flow responses to posture change: implications for athlete recovery

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Running title: Athlete responses to sports compression

Total word count: 3 773

Abstract word count: 198

Number of Tables: 0

Number of Figures: 5

Prepared for European Journal of Applied Physiology

Rationale

Compression garments are proposed to augment arterial blood flow and aid in reducing limb volume. However, these parameters have rarely been assessed in athletic populations, with most research conducted in healthy participants centred around performance and perceptually-based outcomes. Now that the physical characteristics of sports compression garments had been rigorously quantified (Chapters 3 & 4), this study assessed the capacity for them to alter blood flow and limb volume in an active population, as well as taking into account various other cardiovascular parameters. Both sports compression socks and sports compression leggings were investigated to determine whether the different garment types would alter physiological outcomes.

Abstract

Purpose This study aimed to compare the effect of compression socks and compression leggings on lower limb volume, arterial blood flow and central haemodynamics in both supine and upright postures in a healthy, active population.

Methods Eighteen physically active males completed a testing protocol involving three different trials; one wearing a sports compression sock (SOCK), one wearing a sports compression legging (LEG), and one without any compression (CON). Garments were fitted to the right leg while participants were positioned on a tilt table. They lay supine for 5min, before being tilted upright to 60° for 5min, then back to supine for 5min while strain gauges and Doppler ultrasound were used to assess changes in limb volume and arterial flow.

Results Wearing SOCK resulted in a significant increase in limb volume when tilted upright ($p<0.01$), as well as a significant decrease when returned to supine compared to the other two trials ($p<0.01$). In contrast, LEG exhibited no difference to CON other than a reduction in respiratory rate ($p<0.01$). No differences were apparent between trials for acute blood flow measures ($p=0.87$).

Conclusions Compression socks were more effective in reducing limb volume than sports compression legging, which exhibited no differences from a control condition. This unexpected finding may be due to compensatory alteration of the respiratory system.

Keywords sports compression, Doppler ultrasound, strain gauge plethysmography

Introduction

Graduated compression garments are currently a popular tool used by athletes in their pursuit of improved performance and recovery[2,3]. Their proposed benefits originate from the premise that they elicit physiological responses similar to those exhibited by medical compression garments[26]. Medical garments have shown to be particularly effective in producing beneficial outcomes for sedentary and pre-operative populations, but the transferral of these benefits from a clinical to an athletic setting is yet to be clearly illustrated[37].

Compression garments used by sedentary individuals can increase both arterial flow and venous return[39,95]. These changes are brought about by a reduction in vessel diameter, and subsequent increases in flow velocity[8,34,107]. They are particularly beneficial to clinical patients as they assist in limiting deep vein thromboses[108] and reducing oedemas[109] and venous ulcers[12].

Athletic populations are also proposed to benefit from these physiological shifts, albeit via different outcomes. Augmented arterial and venous flow can potentially improve nutrient delivery to fatigued muscles, as well as hastening removal of waste products built up during exercise[38]. Reductions in oedema can also assist in improving recovery from exercise by limiting limb swelling and subsequent muscle soreness[110].

Most research into the use of compression garments by athletes has emphasised performance-based outcomes, with some investigating benefits secondary to the physiological mechanisms underlying their use, such as surrogate measures like heart rate, blood lactate and muscle oxygenation[15,73], inferring changes in venous return. One study did investigate ejection fraction in athletes wearing sports compression stockings[49], reporting them to have no influence on the cardiac parameter. Several factors may have contributed to this unfavourable finding for sports compression garments, and further investigation is required in this area to better understand any possible physiological mechanisms involved.

Research into the efficacy of different length compression garments is also sparse. Knee-length and thigh-length stockings have both been reported to be beneficial to medical patients, with investigators struggling to differentiate between the two[9,108,111,112]. Although a wide variety of garment types have been investigated, the authors are unaware of any research that has compared changes in physiological parameters evoked by different garments.

The aim of this study was to compare the effect of compression socks and compression leggings on lower limb volume, arterial blood flow and central haemodynamics in both supine and upright postures in a healthy, active population. Findings from the study provide a better understanding of the application of compression garments in a sporting setting, and their capacity to aid in athletic performance and recovery.

Methods

Recruitment

Eighteen physically active males (mean ± SD: 394 ± 157 min physical activity.week^{-1}; height 181 ± 8 cm; body mass 82.6 ± 13.0 kg; age 25 ± 5 y) were recruited for this study. All participants were free of cardiovascular conditions and had no history of venous disease, postural hypotension or syncope. Each participant provided informed consent prior to the beginning of data collection. The University and Institute Research Ethics Committees approved the study.

Study Overview

Each participant attended the climate-controlled laboratory (20 ± 1°C) on one occasion, having avoided strenuous exercise for the previous 24 hours and consumed nothing but water for the three hours prior to testing. Lower limb anthropometric measurements (foot size, calf and thigh girths) were taken for each participant so that they could be fitted for sports compression garments according to manufacturers' recommendations. Three different conditions were trialled in a counter-balanced order to minimise any order effect, with at least 15 min separating each trial. The three conditions were: 1) sports compression socks (SOCK; 2XU Elite Compression Sock, Melbourne, Australia); 2) sports compression leggings (LEG; 2XU Compression Leg Sleeve, Melbourne, Australia); and 3) a control trial involving no garment (CON). Each trial required participants to be positioned on a manual tilt table for the assessment of whole limb resting blood flow. Following these measures, participants underwent an orthostatic tilt test, with both whole limb volume and common femoral artery blood flow measurements taken throughout the protocol.

Compression Garments

The compression socks used covered the entirety of the lower limb below the knee, including the foot, and were comprised of a combination of 140-denier nylon and 360-denier elastane fabrics. The leggings ran from the gluteal fold to the distal border of the medial malleolus of the ankle and were manufactured with 250-denier elastane material. Interface pressure applied by the garments was measured 3cm below the maximal calf girth throughout the testing protocol using a Kikuhime Pressure Monitoring Device (MediGroup, Melbourne, Australia)[99]. Compression garments were fitted to the left leg, with the right leg remaining free of compression and used as an internal control.

Whole leg resting blood flow

After being fitted with the appropriate garment, participants were familiarised with the test procedures and then rested quietly in a supine position on a tilt table for 10 min prior to any measurements. Venous occlusion plethysmography (VOP) was used to assess whole leg blood flow[113] in the left leg, then the right leg. Participants were positioned in a supine position with their feet raised slightly to facilitate venous return, and mercury-in-silastic strain gauges were fitted around the maximum calf girth on both legs. Venous occlusion cuffs were positioned around the thighs and connected to a rapid cuff inflator (Hokanson E-20 and AG-101, Bellevue WA, USA). An ankle cuff (~220 mmHg) was used during each measurement to remove any possibility of blood returning from the foot affecting leg volume calculations[114]. For each measurement, the thigh cuff was inflated to 60mmHg for 10s, and blood flow was calculated as the rate of rise in limb volume ($ml.100ml^{-1}.min^{-1}$) over two complete cardiac cycles. Measurements for each limb were performed in triplicate, separated by 20s and averaged. Following resting flow measurements, thigh and ankle pressure cuffs were removed and the strain gauges remained in place around each calf for the assessment of leg volume throughout the orthostatic tilt test.

Orthostatic tilt test

An overview of the orthostatic tilt test is shown in Figure 5.1. Continuous whole-leg volume changes were measured in both limbs, and arterial flow was measured at the common femoral artery of the experimental limb (left) while participants remained supine for 5 min (SUPINE). This was followed by 5 min in an upright position (UPRIGHT, 60° head-up; Figure 5.2), and a further 5 min recovery in the supine position (RECOVERY). Changes in volume of each leg were continuously monitored using plethysmograph strain gauges (Hokanson, USA). Plethysmograph, heart rate (HR, lead II ECG), blood pressure (finger cuff, Finapres Medical

Systems, Amsterdam, The Netherlands) and respiratory rate (RR, respiratory belt transducer) data were continuously collected and stored throughout the test at 400Hz (Powerlab and LabChart7 software, ADInstruments, Bell Vista NSW, Australia). Continuous measurements were averaged over 60s for the assessment of time responses through the test procedures.

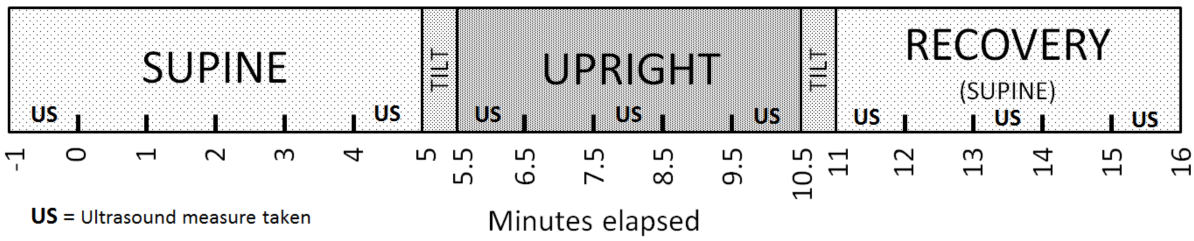

Figure 5.1 Time course of the orthostatic tilt test. Measures began one minute before recording started, with each protocol lasting 16 minutes (three five-minute phases with two 30-s periods allowed for tilting movements).

Common femoral artery blood flow

Duplex ultrasound with continuous Doppler and B-mode imaging (t3000, Terason, Burlington MA, USA) was used to measure arterial blood flow at the beginning, middle, and end of each 5-min phase of the test (Figure 5.1). The left common femoral artery was assessed, distal to the inguinal ligament and ~2cm above the bifurcation into the superficial and profound femoral branch to avoid turbulence from the bifurcation. Recordings were obtained at the lowest possible insonation angle (always below 60°). The sample volume was maximised according to the width of the vessel but kept clear of the vessel walls. For each measurement, Doppler recordings over 10 heart rate cycles were used to obtain a time-averaged mean velocity (v_{mean}, m/s). Vessel diameter (mm) was measured from 2D images with the vessel aligned horizontally, in triplicate, and averaged as the leading-edge to leading-edge distance between the near and far walls of the artery during end-diastole. Arterial flow (AF, $L.min^{-1}$) was calculated from v_{mean}, corrected for its angle of insonation, and multiplied by area (($A = \pi r^2$), m^2) of the femoral artery (AF = v_{mean} * A). Vascular conductance (VC) was calculated as arterial flow divided by mean arterial pressure over the measurement period (VC = AF/MAP).

Figure 5.2 Participant tilted 60º upright while wearing sports compression sock (SOCK). The tilt table was assembled so as to include a foam-padded support between the legs, along with a harness attached to the upper body, allowing participants to be supported in an upright position without the need for a footplate. Leaving the feet unsupported reduced the likelihood of muscle tension in the lower limb as well as limiting the muscle pump formed by the foot and calf musculature, both of which had the potential to confound results[114,115].

Statistical analysis

The SPSS.19® statistical package was used for all analyses. After checking the normality of the variables, a descriptive analysis of the data was performed. One-way ANOVAs were used to determine any differences in acute limb volume measurements (VOP) between conditions and legs. Two-way repeated measures ANOVAs (time*condition) were carried out to assess where significant differences may lie across the time course of the experiment, as well as between conditions, for each dependent variable (limb volume, AF, VC, mean arterial pressure, respiratory rate, heart rate and interface pressure). Experimental plethysmograph data was compared both between legs, with the right leg acting as a control, as well as between conditions. Bonferroni post-hoc analyses were used to determine local specific differences where there were significant main effects or interactions. Significance was set at p=0.05 and results are presented as mean ± standard deviation.

Results

Arterial flow measured by Venous Occlusion Plethysmography

No significant differences in arterial flow, as measured via VOP, were apparent between conditions at rest (p=0.77, Figure 5.3). Similarly, no differences were apparent between limbs for the three conditions (p>0.12).

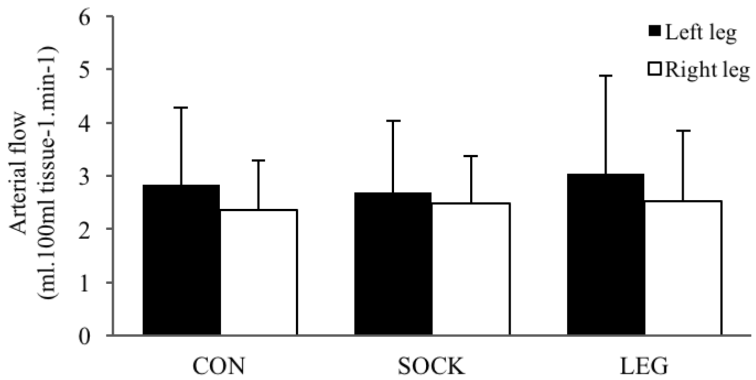

Figure 5.3 Mean ± SD arterial flow (ml.100ml $tissue^{-1}.min^{-1}$) for each of the three conditions; CON (control), SOCK (sports compression sock) and LEG (sports compression legging).
Error bars represent standard deviation of each measure.

Continuous Whole Limb Volume Assessment

Continuous measures taken during the orthostatic tilt test revealed significant differences between conditions in the rate at which limb volume changed. No differences were apparent while participants were SUPINE (p=0.39), however, tilting UPRIGHT caused limb volume to increase significantly more in SOCK than both CON and LEG (p<0.01 for both, Figure 5.4a). There was no difference in limb volume change between CON and LEG when UPRIGHT (p=0.08). When returned to RECOVERY, limb volume decreased significantly more in SOCK than both CON and LEG (p<0.01 for both), while no differences were apparent between CON and LEG (p=0.41). These trends were reflected by comparisons made between legs, with the left leg subjected to the compression intervention and the right leg acting as a control (Figure 5.5).

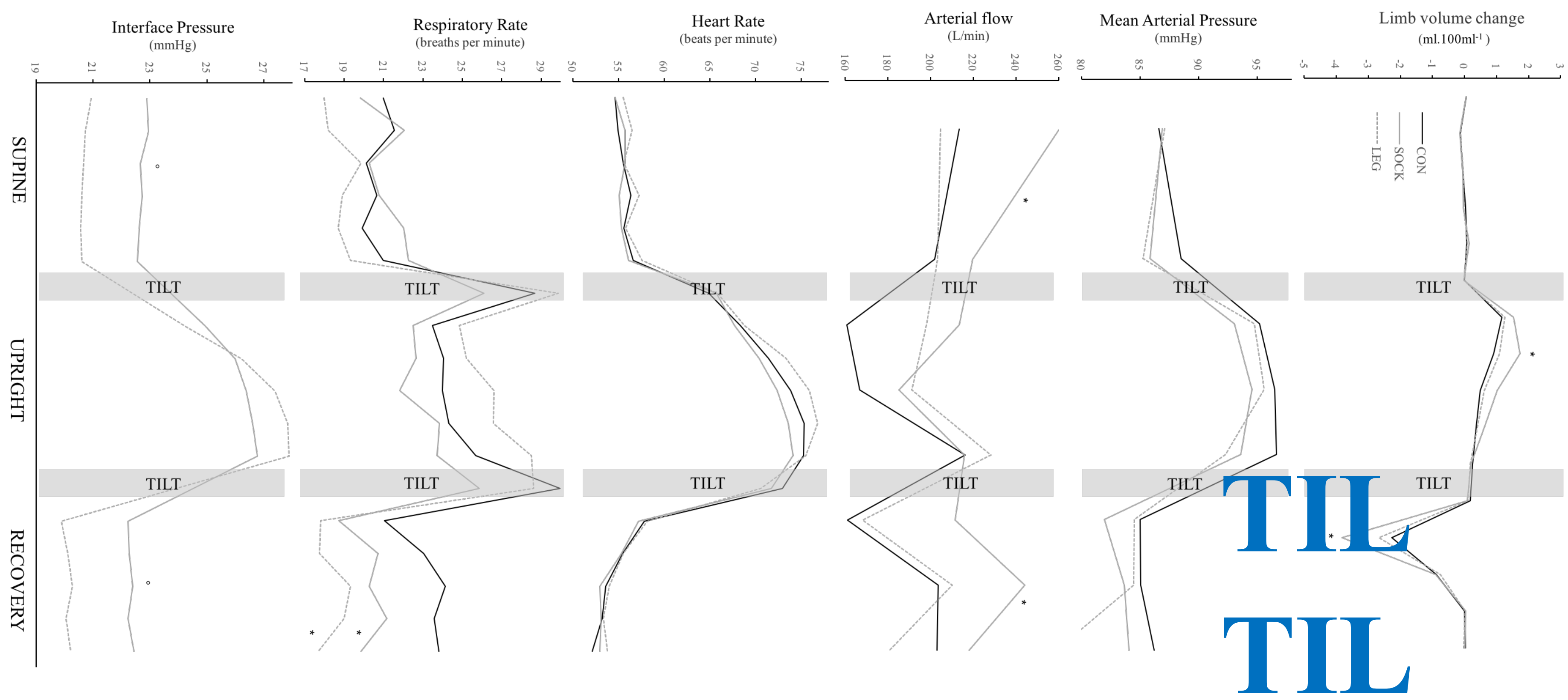

Figure 5.4 Change in limb volume (ml.100ml^{-1}), mean arterial pressure (mmHg), arterial flow (L.min^{-1}), heart rate (beats.min^{-1}), respiratory rate (breaths.min^{-1}) and interface pressure (mmHg) during orthostatic tilt test
*denotes significant difference from CON, ° denotes significant difference from LEG, $p<0.05$

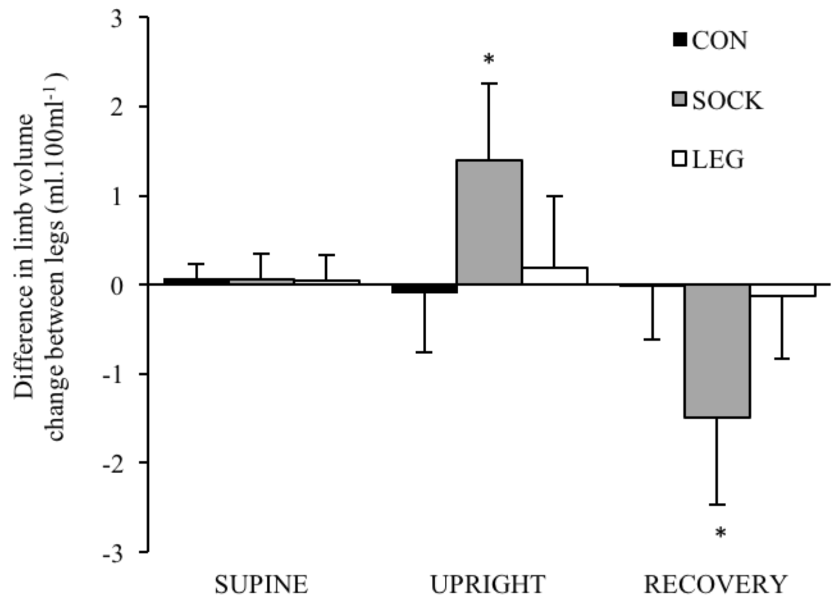

Figure 5.5 Difference in limb volume change between legs (ml.100ml^{-1}) for the three different interventions. Error bars represent standard deviation of each measure. *denotes significant difference from CON and LEG, p<0.05

Mean arterial pressure

MAP increased significantly when participants were UPRIGHT for all three conditions (CON, p=0.02; SOCK, p=0.04; and LEG, p=0.02; Figure 5.4). However, no significant differences were apparent between conditions during the course of the orthostatic tilt test (p=0.24).

Femoral arterial flow and vascular conductance

Experimental condition had a significant impact on AF (p=0.02, Figure 5.4). SOCK resulted in higher AF compared to both LEG and CON when SUPINE and during RECOVERY (p=0.007 and 0.02, respectively). No significant differences were apparent between LEG and CON during the orthostatic tilt test (p=0.06). The interaction of AF and MAP (VC) exhibited no significant differences between conditions or across the course of the experimental protocol (p=0.87).

Heart rate

HR increased when tilted UPRIGHT to a frequency significantly higher than both SUPINE and RECOVERY ($p<0.01$, Figure 5.4). This trend was apparent for all conditions, with no significant differences between the three ($p=1.00$).

Respiratory rate

RR increased significantly upon movement to UPRIGHT ($p<0.01$, Figure 5.4), and dropped away sharply upon RECOVERY ($p<0.01$) for all conditions. CON exhibited significantly higher RR than both SOCK and LEG across the entire orthostatic tilt test ($p<0.01$ for both). No difference was apparent between SOCK and LEG ($p=0.78$).

Interface pressure applied by compression garments

Interface pressure applied by LEG (23.7 ± 3.9mmHg) was significantly higher than SOCK (22.4 ± 4.6mmHg) during SUPINE and RECOVERY (both $p<0.01$, Figure 5.4). However, this trend was not apparent during UPRIGHT, where no significant difference was apparent between the two compression conditions ($p=0.37$).

Discussion

The capacity for sports compression socks to reduce the limb volume of athletes at rest is clearly conveyed by results from the current study. In contrast, sports compression leggings showed little impact on blood flow parameters, bringing into question whether they are effective in an athletic setting[38]. These findings go some way to validating why such equivocal research outcomes have previously been reported by investigations using compression garments.

Acute measures showed no differences between experimental trials, however continuous assessment of changes to limb volume over a longer time period, including changes in posture, were able to differentiate between conditions. The control condition exhibited characteristics symbolic of postural changes, with a large immediate increase in leg volume upon tilting upright[116]. This shift was coupled with increases in mean arterial pressure, heart rate and respiratory rate when tilted upright[117-119].

Sports compression socks followed similar trends, although in a more pronounced fashion, while sports compression leggings were very similar to the control condition. The application of compression socks for exercise recovery bodes well, as they reduced limb volume quickly upon return to a supine position. This is reflective of whole limb blood flow, and a tendency to reduce oedema, as has been illustrated multiple times in clinical populations[96,120]. Surprisingly, whole limb also increased most rapidly in the compression sock condition when tilted upright. This finding is in stark contrast to the authors' hypotheses. It is believed that a tourniquet effect was produced by the elastic cuff at the upper extremity of the sock, allowing augmented inflow (as seen by DU when supine), but suppressing flow out of the calf. Secondary to this justification, the use of a rate of change measure rather than an absolute calf volume assessment may also have influenced results.

Sports compression leggings also exhibited unexpected shifts in haemodynamic measures, with no significant differences when compared to the trajectory of parameters for the control condition. This finding contrasts with the multiple investigations to have reported the capacity of compression leggings to increase venous outflow in sedentary populations[9,95,96]. One recent study did reflect the current findings, with healthy men exhibiting no change in arterial flow when compression garments were worn[37]. The homogeneity of these results further questions the potential for sports compression leggings to positively affect athletic populations.

The absence of a clear disparity between conditions may be a result of changes in respiratory rate, garment coverage or pressure gradient. Respiratory rate was significantly lower in the compression conditions throughout the experimental procedure, suggesting that less cardiovascular strain was required to achieve similar blood flow outcomes when compression was worn. This concept seems more plausible than the difference in garment coverage, as garments covering greater surface area have previously been recognised as producing less cardiac strain[27]. Steep pressure gradients have also been demonstrated to influence the magnitude at which venous return is modulated by compression garments[22,96]. The gradient exhibited by the sports compression sock may suggest that it would be more effective than the sports compression legging.

Conclusion

These results illustrate that the beneficial effects displayed by compression garments in a clinical setting are not strictly replicated when adopted by athletic individuals. However, the capacity for sports compression socks to improve venous flow when athletes are supine, thereby reducing limb volume; bodes well for their ability to improve exercise recovery. Future research should aim to assess correlations between improvements in venous and arterial flow and oedema with improved performance and recovery.

Conflicts of interest

The authors report no conflicts of interest with the present study. The compression garment suppliers (2XU, Melbourne, Australia) had no input into the study design, data collection or analysis, and had no say in the publication of this research.

Acknowledgements

The authors of this paper would like to acknowledge 2XU Australia for supplying the compression garments used for testing.

Chapter 6:

Effect of compression socks worn between repeated maximal running bouts

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Running Title: Compression socks for running recovery

Total word count: 4 000

Abstract word count: 206

Number of Tables: 1

Number of Figures: 3

This chapter has been published as:

Brophy-Williams, N., Driller, M. W., Kitic, C. M., Fell, J. W. & Halson, S. L., Effect of compression socks worn between repeated maximal running bouts, *International Journal of Sports Physiology & Performance*, 2017; 12(5):621-7.

Thomson Reuters Impact Factor (2017): 2.65

3 citations as at February 2018

Rationale

Most research investigating the efficacy of sports compression garments has concentrated on performance outcomes, with the assessment of perceptual measures also common. Unfortunately, these outcomes are not always clearly linked, and the mechanisms underlying their alteration often remain unclear. After displaying the capacity for sports compression garments to reduce limb swelling following orthostatic stress (Chapter 5), this study aimed to assess whether such physiological alterations were large enough to prompt changes in recovery and exercise performance. Multiple parameters were collected, including perceptual, psychological and physiological measures, to better understand the cause of any change in performance.

Abstract

Purpose: To determine the effect of wearing compression socks between repeated running bouts on perceptual, physiological and performance-based parameters.

Methods: Twelve well-trained male runners (mean ± SD; 5km time 19:24 ± 1:19 mm:ss) recorded their perceptions on the efficacy of compression socks for recovery prior to completion of two experimental sessions. Each session consisted of two 5km running time trials (TT1 and TT2) on a treadmill, with a one-hour recovery period between each TT. In a randomised cross-over design, one session required participants to wear compression socks during the recovery period (COMP), while no compression socks were worn between TTs in the other session (CON).

Results: Running performance between TT1 and TT2 in COMP was similar between TTs (mean **Δ** ± SD; 5.3 ± 20.7s, d=0.07, p=0.20) while for CON, performance significantly decreased in the second TT (mean **Δ**; 15.9 ± 13.3s, d=0.19, p<0.01). When grouped by perception of efficacy for compression socks, participants with strong beliefs (n=7) maintained subsequent running performance with COMP (mean $\mathbf{\Delta}$; -3.6 ± 19.2s, d=0.05, p=0.32) compared to those with neutral or negative perceptions who experienced impaired subsequent performance (n=5, mean $\mathbf{\Delta}$; 17.9 ± 17.0s, d=0.19, p=0.04). Cross-sectional area of the calf and muscle soreness were significantly reduced during the recovery period with the use of COMP ($p<0.01$), while ratings of fatigue showed no difference between conditions.

Conclusions: Wearing compression socks between repeated running bouts can aid recovery and subsequent performance. Furthermore, subsequent exercise performance may be even further enhanced when athletes believe in the efficacy of compression socks to assist in recovery between exercise bouts.

Keywords: Recovery, running, time trial

Introduction

Compression garments have long been used in the medical industry for their ability to improve circulation[9], lymphatic flow[94] and venous return[95]. More recently, the use of compression garments has become widespread among athletes with the aim of improving recovery between training bouts[5,14,121,122]. Among the proposed physiological benefits of wearing sports compression garments is an increase in venous return. This increase in venous return allows improved oxygen and nutrient delivery to fatigued muscles and the removal of metabolites that have accumulated during exercise[91]. Compression garments are also proposed to limit inflammation of the limbs by creating an external pressure gradient that limits the space available for swelling to occur, therefore reducing the likelihood of oedema[26,110]. In conjunction with these physiological benefits, compression garments have also recently been proposed to confer additional performance benefits when athletes have positive perceptions of their efficacy[3].

Research into the efficacy of compression garments used post-exercise has produced equivocal results when tested on well-trained athletes[5,26,91]. Scientists consistently report reductions in perceived muscle soreness and improved perceptions of recovery when compression garments are worn post-exercise, whether it be following cycling[14], team sport activity[43,53] or distance running[24,54]. However, these seemingly beneficial effects of compression garments do not always translate into performance benefits, particularly in running activities. Hill and colleagues[54] found no difference in muscular strength throughout the time-course of recovery post-marathon when wearing compression tights compared to a control trial in 24 athletes. Similarly, Bieuzen and colleagues[24] found compression garments to have a *small* effect (d=0.35) on recovering muscular strength 24 hours after a trail run, even after athletes reported positive effects on muscle soreness. In contrast, several investigations have reported compression garments to benefit time trial and sprint performance when worn during a recovery period between exercise bouts, with results ranging from a 2% improvement in 3km running time trials to small, but significant, capacity to maintain cycling time trial performance[14,51,53]. Unfortunately, these investigations often show little or no link between performance gains and possible physiological mechanisms that may explain these benefits. A recent comprehensive review by Born and colleagues[1] confirmed this view, reporting the highly variable impact of compression garments worn post-exercise on physiological parameters, albeit recognising their potential to have a benefit on time to exhaustion and time-trial (TT) performances.

These equivocal and somewhat contradictory findings beg the question of whether physiological mechanisms provoked by the use of compression garments are in fact providing an impact on recovery and subsequent performance, or whether psychological factors may play a role in their efficacy. Duffield and colleagues[42] suggested that the placebo effect needs to be considered, as athletes in their investigation reported reduced muscle soreness, while no differences in physiological or performance measures were apparent. Therefore, it is postulated that the athletes' prior belief in the ability for compression garments to aid performance may also play a role in the observed outcome. Although Stickford and colleagues[46] reported that wearing compression socks during running had no clear effect on economy, the authors noted that individual responses were highly varied and were closely related to the athlete's belief in the efficacy of the garments. This particular investigation looked at the use of compression garments during exercise, rather than in a recovery setting, but it introduces the possibility that an athlete's belief in the ergogenic properties of compression garments, among a multitude of factors, may influence performance. This is further reinforced by a recent review that remarked on study participants' likely positive perceptions and intuitions regarding the potential for compression garments to improve performance[3].

The current study aimed to assess the effect of wearing compression socks during a one-hour recovery period following a 5km running TT on performance in a subsequent 5km TT. Investigators were acutely aware of collecting data on a myriad of parameters so as to better understand the relationships between these factors and their impact on athletic performance.

Methods

Participants

Twelve well-trained male runners (mean ± SD; 5km run time 19:29 ± 1:18 min:sec, height 181.4 ± 6.9 cm, body mass 77.8 ± 6.5 kg, age 30.5 ± 8.1 years) who had a training history of at least four training runs per week for the past three years were recruited for the current study. This number of participants was based on the required sample-size, as identified by the calculation methods outlined by Atkinson[123]. All participants were briefed on the requirements of taking part in the study before informed consent was provided. The Australian Institute of Sport and University of Tasmania Human Research Ethics Committees approved the study prior to data collection commencing.

Study design

Each participant attended the climate-controlled laboratory (21 ± 1°C) on three occasions: one familiarisation session and two experimental sessions. The experimental sessions were administered in a counter-balanced, crossover design. In order to control any dietary variables, participants completed a 24 h food diary prior to their first experimental session and were instructed to replicate their diet as closely as possible before the subsequent experimental session. Training was also controlled for, with participants keeping all training identical for 48 h before testing on all occasions. Participants were asked to refrain from strenuous exercise (<24 h) and caffeine (<12 h) and to arrive in a fully rested, hydrated state. All testing was performed on the same treadmill at the same time of day to minimize diurnal variation. Each experimental session involved participants performing a standardised warm-up followed by a 5km TT (TT1), then a one-hour recovery intermission before a second warm-up and 5km TT (TT2). Familiarisation sessions involved the completion of just one warm-up protocol followed by a single 5km TT.

Belief Effect

Prior to their familiarisation session, participants were asked to rate their perceptions on whether "compression socks improve recovery between repeated running bouts" on a continuous 10cm visual analogue scale, ranging from "strongly disagree" (0cm) to "strongly agree" (10cm). Care was taken throughout the experimental period so as not to influence participants' perceptions of the use of compression garments. All participants had prior experience wearing compression garments before taking part in the current study.

5km Time-Trials

The exercise protocol is outlined in Figure 6.1. The warm-up consisted of three four-minute blocks of submaximal running at 60, 70 and 80% of participant-reported 5km race pace (mean speeds of 9.6 ± 0.6, 11.1 ± 0.7 & 12.7 ± 0.8km.h^{-1}, respectively) on a custom-built, motorized treadmill (Australian Institute of Sport). Prior to the commencement of the study, the treadmill was calibrated using first principles. A rest period of one-minute was implemented between each warm-up intensity. Following the warm-up, participants completed a maximal 5km TT on the same treadmill (TT1). The same warm-up and a subsequent 5km TT was performed 60-

minutes later (TT2). The TTs began at a speed 1km.h^{-1} slower than the predicted mean speed required for completion of a 5km road race, as previously reported by participants. During the 5km TT, participants were blinded to their elapsed time and run speed, and standardised, scripted encouragement was given by the researcher every 500m. Participants were to indicate to the researcher for the speed to increase or decrease at any stage of the test by saying ‘faster’ or ‘slower’. Participants were also partially blinded to distance covered, with progress revealed every 500m up until the final 500m, whereupon they received updates for each 100m run. Total time was recorded at the completion of the 5km TTs and the difference between TT1 and TT2 was used as the main performance outcome measure. The reliability of the 5km TT has been previously determined, with a typical error of 10.9 seconds and coefficient of variation of 1.0% following just one familiarisation session in a group of male runners similar to the cohort used in the current study[124].

Figure 6.1 Experimental protocol. Warm-up intensities based on 60, 70 and 80% of self-predicted 5km road race pace. COMP = compression condition (wearing compression socks); CON = control condition (no compression socks).

Recovery period

During the 60-minute recovery period a carbohydrate drink (Gatorade; 6% carbohydrate content) and muesli bars (Uncle Toby’s; 20.5g carbohydrate per bar) were provided to participants to be consumed ad libitum in their first experimental session, with consumption levels matched for the subsequent experimental session. The recovery period was spent under one of two conditions: compression (COMP) or control (CON). COMP involved wearing commercially-available sports compression socks (2XU Elite Compression Sock, Melbourne, Australia). Lower limb anthropometric measurements were taken for each participant so that they could be fitted for sports compression garments according to manufacturers' recommendations. Pressure applied by the garment was assessed at three landmarks on the right leg, previously validated by Brophy-Williams and colleagues[102], using the valid and reliable Kikuhime pressure monitoring device[99] (MediGroup, Melbourne, Australia) so as to reveal a clear pressure profile of the garment. Mean pressure (± SD) of the compression socks was 23 ± 11mmHg at the maximal calf girth, 22 ± 8mmHg at the upper ankle and 19 ± 8mmHg at the lower ankle. No compression socks were worn during CON. Participants remained in a passive, seated position in the temperature-controlled laboratory for the duration of the recovery period in both conditions.

Outcome Measures

Blood lactate concentration (BLa) was measured via a capillary fingertip sample and was analysed with a Lactate-Pro 2 analyser (Arkray, Shiga, Japan). Samples were collected three minutes after the completion of TT1, and again at the end of the 60-minute recovery intermission between TTs.

Three-dimensional (3D) laser body scans (Vitus Smart XXL, Human Solutions; Kaiserslautern) were used to accurately assess any changes in cross-sectional area of the calf[125]. Repeat scans were taken without compression immediately after TT1 and again five-minutes prior to the commencement of the second warm-up. The Vitus Smart XXL 3D scanner has been reported to produce highly accurate and reproducible results[126].

At the beginning and conclusion of the recovery period, athletes performed a half-squat exercise, as described by Vaile and colleagues[127], to promote general body awareness before rating their perceived muscle soreness and fatigue on a 10-point visual analogue scale (from 'no soreness at all' to 'extremely sore' and 'no fatigue at all' to 'extremely fatigued', respectively). Participants also rated their perceived recovery on the Total Quality Recovery scale (TQR)[128] at the start and end of the recovery period.

Statistical Analysis

SPSS Statistics Package (SPSS Statistics IBM, Version 20.0) was used to assess data for normality, and to confirm that the Kolmogorov-Smirnov test for normality and Mauchly's Test of Sphericity were not violated. Data plots were visually assessed for outliers. A paired t-test was used to determine that no order effect was apparent for the two conditions. Two-way ANOVAs (time*condition) were then performed to assess where significant differences may lie across the time course of the experiment, as well as between conditions, for each dependent variable. Post-hoc analyses (bonferroni-corrected t-tests) were used to determine where specific differences occurred. The change from pre to post-recovery was also compared between conditions with a paired t-test. Cohen's effect sizes (*d*) were calculated where appropriate.

Data was then divided into two groups according to whether participants had positive perceptions of the efficacy of compression socks for recovery ('believers', ≥60% belief in their ability to aid recovery on visual analogue scale) or neutral to negative perceptions ('non-believers', <60% belief in efficacy). Previous analyses were performed again on these sub-groups to determine the effect of athlete belief on both perceptual and performance-based outcomes. Run performance times were log-transformed to reduce bias arising from nonuniformity of error. Practical differences in performance between these sub-groups were then identified using a magnitude-based inference approach on the log-transformed data, with change scores converted into standardised (Cohen) effect size scores and interpreted using the following criteria: <0.2, *trivial*; 0.2-0.6, *small*; 0.6-1.2, *moderate*; 1.2-2.0, *large*; >2.0, *very large*[100]. Standardized changes in the mean of each measure were used to assess magnitudes of effects and provide the likelihood of the true effects being practically positive, trivial and negative by dividing the changes by the smallest worthwhile change[129]. As identified previously, the smallest worthwhile change for the performance test was deemed to be 1.0% (unpublished observations). All results are presented as mean ±95% confidence limits unless otherwise stated. Statistical significance was set at $p < 0.05$.

Results

Run performance in TT2 was significantly slower than TT1 for CON (d=0.19 ±0.67, p<0.01, Figures 6.2 & 6.3). In contrast, no difference was apparent between TT1 and TT2 for COMP (d=0.07, p=0.20). COMP had a *moderate*, but non-significant (d=0.62, p=0.14) effect on reducing performance decrement compared to CON. No order effect was apparent for the two conditions (p=0.08).

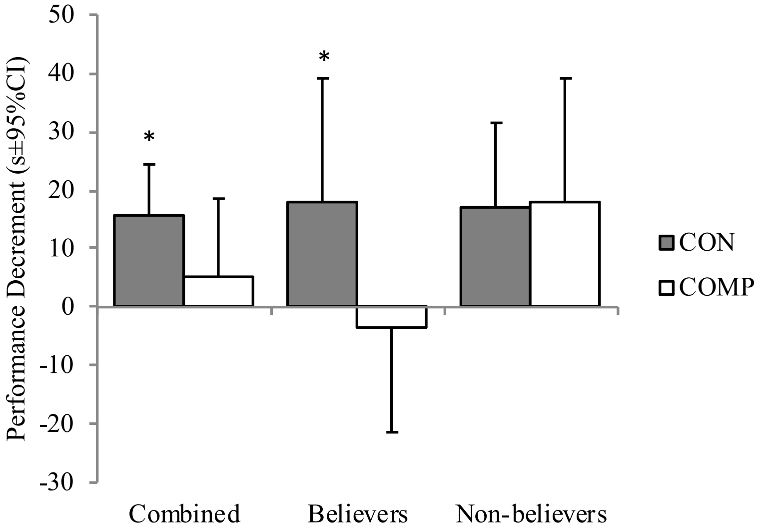

Figure 6.2 Mean performance change (s ±95% Confidence Limits) from time-trial 1 (TT1) to time-trial 2 (TT2) for all participants (combined), and subgroups of 'believers' (n=7) and 'non-believers' (n=5) in control (CON) and compression (COMP) conditions. *denotes significant difference from COMP condition within group/subgroup ($p<0.05$).

There was no significant interaction between time and condition for muscle soreness ($p=0.32$), but a main effect was exhibited for time ($F(3,44)=3.035$, $p=0.09$). Post-hoc analyses revealed COMP to have a *moderate* and significant impact on reducing muscle soreness in the recovery period ($d=0.79$, $p<0.01$), while CON had no effect ($d=0.09$, $p=0.30$, Table 6.1).

Table 6.1 Mean time (s ±95% Confidence Limits) for the two time-trials (TT1 and TT2) and for the variables measured before and after the 60-minute recovery period for the compression (COMP) and control (CON) conditions.

	CON (Mean ±95% Confidence Limits)	COMP (Mean ±95% Confidence Limits)	ΔCON - ΔCOMP (% ±95% Confidence Limits and Effect Size)
TT1 (min:sec.ms)	19:24.6 ±0:51.5	19:34.4 ±0:48.1	0:10.6 ±0:14.5 Moderate
TT2	19:40.5 ±0:53.3	19:39.7 ±0:48.3	
Pre-recovery MS (AU)	3.8 ±1.2	4.8 ±1.3	-2.3 ±1.5* Large
Post-recovery MS	4.0 ±1.3	2.8 ±0.7	
Pre-recovery Fatigue (AU)	5.4 ±1.5	5.3 ±1.3	-0.6 ±1.0 Small
Post-recovery Fatigue	3.6 ±1.1	2.9 ±0.9	
Pre-recovery TQPR (AU)	10.6 ±2.9	11.8 ±2.0	-0.3 ±1.8 Trivial
Post-recovery TQPR	13.9 ±1.3	14.8 ±0.8	
Pre-recovery CSA (cm^2)	116.7 ±7.0	115.8 ±7.1	-1.0 ±0.9* Moderate
Post-recovery CSA	115.8 ±7.6	113.9 ±7.3	
Pre-recovery La ($mmol.L^{-1}$)	9.2 ±1.7	9.8 ±2.1	-0.5 ±1.9 Trivial
Post-recovery La	2.5 ±0.6	2.6 ±0.7	

MS = Muscle soreness; TQPR = Total Quality Perceived Recovery; CSA - Cross sectional area; La = Blood lactate concentration; AU = arbitrary units. * = Significant difference (P<0.05).

No interaction between time and condition was present for fatigue (p=0.60). There was a main effect for time (F(3,44)=14.771, p<0.01), but not for condition (p=0.50). Post-hoc analyses showed a *small*, but non-significant reduction in fatigue in the COMP condition (*d*=0.26, p=0.24).

Perceived recovery was not significantly affected by the interaction of time and condition (p=0.85). A main effect was apparent for time on perceived recovery (F(3,44)=13.226, p<0.01), but not condition (p=0.26). Post-hoc analyses revealed *small* and *moderate* significant improvements in perceived recovery for CON and COMP, respectively, from the start to the end of the recovery period (CON: *d*=0.44, p=0.01; COMP: *d*=0.78, p<0.01).

Calf CSA exhibited no interaction effect between time and condition ($p=0.88$) or main effects for either time ($p=0.67$) or condition ($p=0.68$). However, post-hoc t-tests showed COMP to have a *large*, significant effect on reducing calf CSA ($d=0.74$, $p=0.01$).

No interaction effect between time and condition was apparent for blood lactate ($p=0.71$), but there was a main effect for time ($F(3,44)=114.074$, $p<0.01$). Post-hoc analyses showed *large* significant reductions in blood lactate during the recovery intermission for both CON ($d=1.97$, $p<0.01$) and COMP ($d=1.85$, $p<0.01$), but revealed no significant differences between conditions ($d=0.18$, $p=0.29$).

Dividing participants into 'believers' (n=7) and 'non-believers' (n=5) reflected two distinctly different responses to the use of compression garments. Run performance of 'believers' was significantly slower in TT2 compared to TT1 in CON ($d=0.23$, $p=0.02$), yet there was no significant decrement in performance in COMP ($d=0.05$, $p=0.32$, Figures 6.2 & 6.3). Run performance of 'non-believers' declined from TT1 to TT2 regardless of condition, with both CON and COMP exercise sessions resulting in *trivial*, but significant, performance decrements ($d=0.14$, $p=0.02$ & $d=0.19$, $p=0.04$ respectively). The difference in performance decrement between the 'believers' and 'non-believers' was considered to have a *small* effect size (10.6 ±14.5s, $d=0.25$, $p=0.07$), with COMP likely to have a positive effect on performance (79% positive:20% trivial:1% negative) for the 'believers'.

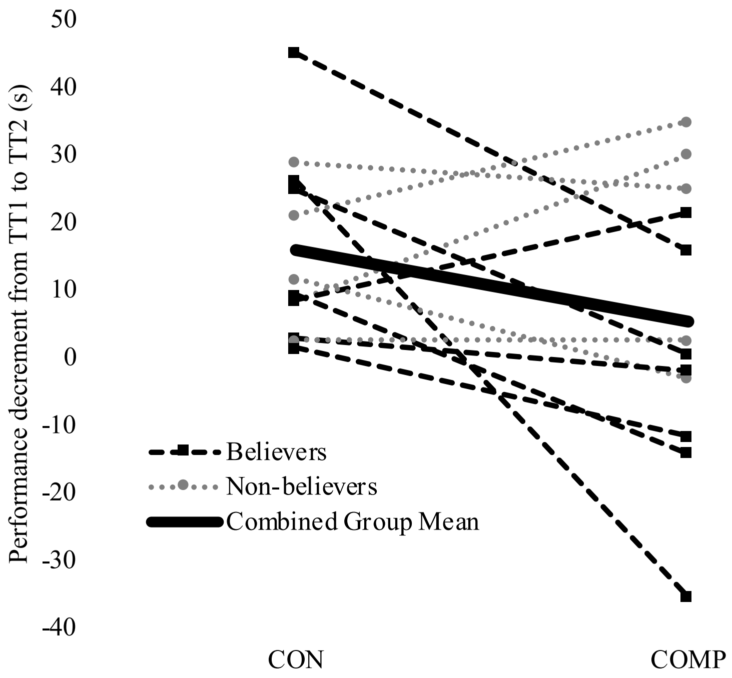

Figure 6.3 Individual performance decrements under both control (CON) and compression (COMP) conditions (s).

When perceptual measures were analysed with data grouped as above, significant reductions in muscle soreness were exhibited in COMP by both ‘believers’ (*d*=0.63, p=0.05) and ‘non-believers’ (*d*=2.83, p=0.02).

There was a significant, but *trivial* reduction in ‘believers’ perception of fatigue in the COMP trial (*d*=0.18, p=0.04), while ‘non-believers’ experienced a *small*, but non-significant effect on fatigue with COMP (*d*=0.26, p=0.36).

Discussion

Results from the current study suggest that compressions socks might aid recovery between exercise bouts. Evidence is also provided to support the theory that a belief effect may influence the ergogenic effect of compression garments. To the authors’ knowledge, this is the first study to have assessed the potential for compression garments to improve recovery between repeated

5km running efforts, while taking into account physiological, perceptual and performance-based parameters.

It is also the first study to investigate compression garments in an open-loop running task, such as a TT, in controlled laboratory conditions. These conditions were decided upon so as to replicate a maximal effort while controlling as many factors as possible so that any differences measured in performance could more easily be accounted for by the intervention rather than external factors, such as may be the case for trail running[70] and investigations using fixed workloads or submaximal efforts[67,130]. Under these laboratory-controlled conditions (21 ± 1°C), the effect of compression socks on performance recovery was synonymous with findings by Driller & Halson[14] and de Glanville & Hamlin[51], who also reported positive effects from wearing compression garments between exercise bouts.

Most interestingly, participants' perceptions on the efficacy of the garments for exercise recovery seems to have played a large role in determining whether compression socks provided performance benefits for their users. Stickford and colleagues[46] provides the only previous investigation to have assessed participants' beliefs in the efficacy of the garments, alluding to the idea of variable individual responses possibly dependent on perception, albeit no overall changes were reported for the population tested. Duffield and colleagues[42] commented on the possibility of a placebo effect being present when using compression garments but did not examine this. The current study showed that the majority of participants with positive perceptions of compression socks for recovery appeared to benefit, reflected in the maintenance of subsequent running performance when in the COMP condition. In contrast, most of those with negative, or even neutral perceptions, showed a decline in subsequent performance, regardless of intervention. The theory of a belief effect and its impact on human performance has previously been detailed by Halson & Martin[131], and it seems that such an effect may well have impacted on the key performance outcome of this investigation. The potential for the apparent belief effect occurring is further supported by the concept presented by McClung & Collins[59], whereby expectancy plays a major role in the success of interventions in the field of high-performance sport. Ergogenic benefits expected by 'believers' in the current study resulted in a smaller performance decrement when COMP was worn[12].

Blood lactate did not differ between conditions throughout the recovery period, reflecting the results of de Glanville & Hamlin[51] who reported that compression tights did not affect blood lactate clearance in the 30min period after a 40km cycling time-trial. This suggests that the metabolic activity was similar between conditions and adds further evidence to support the notion that changes in performance are not brought about purely by physiological mechanisms.

A 3D scanner was used in the current study in a novel attempt to accurately assess fluctuations in calf CSA. Previous investigations have assessed calf girth changes using less accurate or practical tools such as tape measures[81] and water displacement[125]. Change in calf CSA was the only measured physical parameter that may be associated with the maintenance of run performance, with greater reductions in CSA in the COMP condition apparent in the current study. Participants' belief had no impact on this variable. The reduction in CSA aligns with the findings of Born et al.[1], who reported reductions in limb girth when compression garments were worn post-exercise. It is proposed that this reduction is likely to be a result of compression garments limiting the space available for swelling and inflammation to occur[26]. This reduction in swelling reduces the impact of muscle damage from prior exercise, as oedema formation is limited, ultimately aiding in subsequent performance[26]. However, it must also be recognised that there was no pre-TT1 CSA measurement, and therefore a chance that changes in CSA presented may also be reflective of fluid shifts to more proximal parts of the body via the calf venous pump[132].

Participants' perceptions of muscle soreness were reduced by the use of compression socks, similar to the majority of the findings in the current literature, where most investigations have reported favourable perceptual outcomes when compression garments have been worn between exercise bouts[26,43,53,133]. These perceptions were present regardless of prior beliefs on the efficacy of compression garments to aid recovery, which may be due to a shift in participants' beliefs during the course of the investigation, or indeed multiple other factors, such as physiological mechanisms that were not measured in the current study. It must be noted that non-elite athletes have a lower tolerance for pain than elite athlete, and therefore may be pre-disposed to reporting greater reductions in muscle soreness in the present study[134].

In contrast, participants perceived no difference in fatigue or recovery between conditions in the one-hour break between TTs. The short period between exercise bouts may not have allowed the full potential of the compression socks to be realised, hence further research is required to better understand the role of compression garments in combating fatigue as it is rarely reported on in the literature.

Practical Applications

Findings from the current study suggest that athletes should employ the use of compression garments between exercise bouts to improve recovery and enhance subsequent performance. Athletes' beliefs in the efficacy of compressions garments may also play a role in their ability to aid performance. We acknowledge that, although very challenging in nature, no placebo condition was used in the current study. It also must be recognised that the assessment of a more extensive array of physiological parameters, such as venous return and inflammatory markers in the blood, may have uncovered factors contributing to improved performance that were not evident in the current study. Further research will assist in investigating the relationship of compression garments and the belief effect in well-trained athletes, as well as further physiological mechanisms that may influence changes in performance, and the interaction between these various factors.

Conclusion

This investigation has shown that compression socks were able aid recovery between repeated running bouts, particularly when athletes believed in their efficacy to do so. Regardless of these beliefs, compression socks effectively reduced swelling in the lower limb and muscle soreness.

Acknowledgements

The authors acknowledge 2XU (Melbourne, Australia) for supplying the compression garments used in this study. 2XU had no input into the study design, data collection or analysis, and had no say in the publication of this research.

Chapter 7:

Wearing compression socks during exercise aids subsequent performance

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Running Title: Compression aids subsequent performance

Total word count: 3 054

Abstract word count: 171

Number of Tables: 3

Number of Figures: 2

This chapter has been published as:

Brophy-Williams, N., Driller, M. W., Kitic, C. M., Fell, J. W. & Halson, S. L., Wearing compression socks during exercise aids subsequent performance, *Journal of Science and Medicine in Sport,* 2018 (In Press).

Thomson Reuters Impact Factor (2017): 3.86

Rationale

The capacity for compression garments to aid athletes has commonly been assessed from one of two aspects; (i) their effect on recovery when worn post-exercise, and (ii) the impact they have on performance when worn during exercise. However, their capacity to influence subsequent exercise performance when worn during an initial bout is an aspect that is rarely evaluated. Following our previous study (Chapter 6), where compression garments were found to aid subsequent running capacity when worn post-exercise, this investigation aimed to assess whether compression garments worn during exercise would affect subsequent running time trial performance. Again, a variety of parameters were measured so as to best comprehend any changes brought about by the use of sports compression socks. This range included physiological, perceptual and psychological variables.

Abstract

Objectives: To assess the effect of wearing compression socks on immediate and subsequent 5km running time trials, with particular attention to the influences on physiological, perceptual and performance-based parameters.

Design: Counter-balanced cross-over experiment.

Methods: Twelve male runners (mean ± SD 5km run time 19:29 ± 1:18 min:sec) each completed two experimental sessions. Sessions consisted of a standardised running warm-up, followed by a 5km time trial (TT1), a one hour recovery period, then a repeat of the warm-up and 5km time trial (TT2). One session required the use of sports compression socks during the first warm-up and time trial (COMP), while the other did not (CON).

Results: The decline in run performance in CON from TT1 to TT2 was *moderate* and significantly greater than that experienced by runners in COMP (9.6s, d=0.67, $p<0.01$). Oxygen consumption, blood lactate, calf volume and perceived muscle soreness, fatigue and recovery did not differ between experimental conditions ($p=0.61$, 0.54, 0.64, 0.56, 1.00 & 0.61, respectively).

Conclusions: Wearing sports compression socks during high intensity running has a positive impact on subsequent running performance. The underlying mechanism of such performance enhancement remains unclear, but may relate to improved oxygen delivery, reduced muscle oscillation, superior running mechanics and athlete beliefs.

Keywords: Running, time trial, athletes, circulation, economy

Introduction

Compression garments have long been used in the medical industry for their ability to improve circulation[9], and therefore, venous return[95]. More recently, the use of compression garments has become widespread among athletes in both performance and recovery-based settings[5], with a wide range of garment types investigated, including knee-high socks, calf sleeves, shorts, tights and upper body compression[5]. Sports compression garments are proposed to reduce muscle oscillation when used during exercise, and hence limit muscle damage; as well as improving running economy, therefore proving beneficial to performance[3,6].

Changes in running economy brought about by compression garments may be related to several mechanisms, including reductions in metabolic requirements, greater proprioception and increased muscular support[61,73]. Two investigations have revealed no changes in the metabolic cost of running when compression garments encapsulating the calves were worn while running at submaximal speeds[13,46]. However, Bringard and colleagues[45] found improved running economy at 12km.hr^{-1}, yet not at faster or slower speeds. These equivocal findings suggest that the precise mechanisms behind potential improvements in running economy are yet to be clearly elucidated, and other changes, such as enhanced proprioceptive feedback and psychological factors, brought about by compression garments may influence outcomes.

The capacity for compression garments to increase venous return is proposed to allow more efficient oxygen delivery to fatigued muscles, hasten the removal of metabolites built up during exercise[3], and therefore reduce cardiac load for a set work output[13]. This reduction in metabolic cost can be illustrated through surrogate measures such as lower blood lactate and heart rate for a given workload[13]. However, these findings seem to be contrary to the norm, with recent reviews concluding that compression garments have little or no effect on blood lactate and heart rate[1,5]. It is likely that any small changes brought about by compression garments during exercise are overshadowed by the large increase in blood flow to the limbs during exercise, which may be up to 10-fold compared to rest[135].

Performance may be enhanced by the increase in proprioceptive feedback provided by compression garments[136]. Improved proprioception allows for more efficient movement, as has been illustrated by the capacity for below-knee compression socks to increase movement accuracy[137]. Movement efficiency is particularly relevant to endurance-based activities like distance running, that require thousands of repeated cyclical actions.

Reducing muscle oscillations during exercise is also proposed to improve movement efficiency[45]. Compressions shorts have been shown to support the muscle belly and reduce movements during training[71,138]. This reduction in movement may promote lower energy expenditure[45]. However, no clear link has been forged between changes in muscle oscillation and endurance performance, as research in this area has focused primarily on explosive sprinting and jumping movements while wearing compression applied to the upper leg[139]. While the link between muscle oscillation and endurance performance is unclear, it is possible that exercise associated inflammation and soreness could be limited by a reduction in muscle movement[64]. Although several investigators[21,45] have alluded to this phenomenon, no clear connection has been displayed between changes in muscle oscillation, improved recovery and subsequent performance.

This study aimed to assess the effect of wearing compression socks during a 5km running time trial on physiological, perceptual and performance-based parameters. In addition, the capacity for compression socks to impact subsequent performance was also investigated.

Methods

Twelve well-trained male runners (mean ± SD; 5km run time 19:29 ± 1:18 min:sec, height 181.4 ± 6.9 cm, body mass 77.8 ± 6.5 kg, age 30.5 ± 8.1 years) participated in the current study. All runners were briefed on the requirements of taking part in the study before consent was provided. The study procedures complied with the Declaration of Helsinki and were approved by the Australian Institute of Sport and University of Tasmania Human Research Ethics Committees prior to data collection commencing.

Each runner attended a climate-controlled laboratory on three occasions: one familiarisation session and two experimental sessions. The experimental sessions were administered in a counter-balanced, crossover design. In order to control any dietary variables, runners completed a 24 h food diary prior to their first experimental session and were instructed to replicate their diet as closely as possible before the subsequent experimental session. Training was also controlled for, with runners keeping all training identical for 48 h before testing on all occasions. Runners were asked to refrain from strenuous exercise (<24 h) and caffeine (<12 h) and to arrive in a fully rested, hydrated state. All testing was performed on the same treadmill at the same time of day to minimize diurnal variation, and participants wore the same footwear and exercise attire for every session. Each experimental session involved runners performing a standardised warm-up followed by a 5km TT (TT1), then a one-hour recovery intermission before a second warm-up and 5km TT (TT2). Familiarisation sessions involved the completion of just one warm-up protocol followed by a single 5km TT.

Runners completed one experimental session wearing new compression socks (Performance Run Sock, 2XU, Melbourne, Australia) for the first warm-up and TT1 (COMP), and one experimental session with no compression socks (CON). Calf girth and foot size were measured for each runner so that they could be correctly fitted for sports compression garments according to manufacturers' recommendations. Pressure applied by the garment was assessed at three landmarks on the right leg, using the valid and reliable Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia). Mean pressure (± SD) of the compression socks was 37 ± 4mmHg at the maximal calf girth, 31 ± 4mmHg at the upper ankle and 23 ± 4mmHg at the lower ankle, measured prior to the beginning of the COMP trial.

The exercise protocol is outlined in Figure 1. The warm-up consisted of three four-minute blocks of submaximal running at 60, 70 and 80% of runner-reported 5km race pace (mean speeds of 9.6 ± 0.6, 11.1 ± 0.7 & 12.7 ± 0.8km.h^{-1}, respectively) on a custom-built, motorized treadmill (Australian Institute of Sport). A rest period of one-minute was implemented between each warm-up intensity. Following the warm-up, runners completed a maximal 5km TT on the same treadmill (TT1). The same warm-up and a subsequent 5km TT was performed 60-minutes later (TT2). The TTs began at a speed 1km.h^{-1} slower than the predicted mean speed required for completion of a 5km road race, as previously reported by runners. During the 5km TT, runners were blinded to their elapsed time and run speed, and standardised, scripted encouragement was given by the researcher every 500m. Runners were to indicate to the researcher for the speed to increase or decrease at any stage of the test by saying 'faster' or 'slower', whereby speed was adjusted by 0.5km.h^{-1}. Runners were also partially blinded to distance covered, with progress revealed every 500m up until the final 500m, whereupon they received updates for each 100m run. Total time was recorded at the completion of the 5km TTs and the difference between TT1 and TT2 was used as the main performance outcome measure. The reliability of a 5km TT has been previously determined in our laboratory, with a typical error of 10.9 seconds and coefficient of variation of 1.0%.

Figure 7.1 Experimental protocol. Warm-up intensities based on 60, 70 and 80% of self-predicted 5km road race pace. COMP = compression condition (wearing compression socks); CON = control condition (no compression socks).

During the 60-minute recovery period a carbohydrate drink (Gatorade; 6% carbohydrate content) and muesli bars (Uncle Toby's; 20.5g carbohydrate per bar) were provided to runners to be consumed ad libitum in their first experimental session, with consumption timing and amounts matched for the subsequent experimental session. Runners remained in a passive, seated position for the duration of the recovery period in both conditions.

Expired air was analysed throughout all three stages of the first warm-up using a custom-built open-circuit indirect calorimetry system with associated in-house software (Australian Institute of Sport). The final minute of each collection was used to assess running economy.

Blood lactate concentration (BLa) was measured via a capillary fingertip sample using a Lactate-Pro 2 analyser (Arkray, Shiga, Japan). Samples were collected at the completion of each stage of the warm-up protocol, as well as three minutes after the completion of both TT1 and TT2. Ratings of Perceived Exertion (RPE) were also collected at these time points.

Three-dimensional (3D) laser body scans (Vitus Smart XXL, Human Solutions; Kaiserslautern) were used to assess any changes in cross-sectional area of the calf. Repeat scans were taken without compression before the first warm-up and immediately after TT1. The Vitus Smart XXL 3D scanner has been reported as accurate and reliable[126].

Before and after each warm-up and TT, runners performed a half-squat exercise, as described by Vaile and colleagues[127], to promote general body awareness before rating their perceived muscle soreness and fatigue on a 10-point visual analogue scale (from ‘no soreness at all’ to ‘extremely sore’ and ‘no fatigue at all’ to ‘extremely fatigued’, respectively). Runners also rated their perceived recovery on the Total Quality Recovery scale (TQR)[128] at the start and end of the recovery period.

SPSS Statistics Package (SPSS Statistics IBM, Version 20.0) was used for all data analyses. Normality was tested with the Kolmogorov-Smirnov test and violations of the assumption of sphericity were determined using Mauchly’s Test of Sphericity. No violations were apparent. A paired t-test was used to determine that no order effect was apparent for the two conditions, with further t-tests to assess differences in time trial performance. Two-way repeated measures ANOVAs (time point*condition) were then performed to determine main effects for each of the remaining dependent variables (blood lactate, expired gases, calf CSA and perceptual assessments). Post-hoc analyses (t-tests) with Bonferroni corrections determined where specific differences occurred.

Practical differences in performance between conditions were identified by calculating standardised (Cohen’s *d*) effect size scores and interpreting them using the following criteria: <0.2, *trivial*; 0.2-0.6, *small*; 0.6-1.2, *moderate*; 1.2-2.0, *large*; >2.0, *very large* [100]. All results are presented as mean ±95% confidence limits unless otherwise stated.

Results

There was no significant difference in TT1 or TT2 performance between conditions (Table 1). A significant, yet *trivial*, decrement in run performance from TT1 to TT2 was evident for CON, while the change in performance in the COMP condition was considered to be *trivial* and non-significant. However, there was a *moderate* significant performance benefit for COMP when comparing the decline in run performance from TT1 to TT2 between conditions. No order effect was apparent for the two conditions (p=0.07).

Table 7.1 Summary of time trial performances for (CON) and compression (COMP) conditions. *denotes significant difference, p<0.05

	CON (mean ± SD)	COMP (mean ± SD)	Difference between conditions
TT1	19:24 ± 0:51	19:32 ± 0:48	No difference (p=0.18, *d*=0.10)
TT2	19:41 ± 0:53	19:38 ± 0:53	No difference (p=0.75, *d*=0.03)
Decrement from TT1 to TT2	15.9 ± 8.5s* (p<0.01, *d*=0.19)	6.4 ± 1.9s (p=0.08, *d*=0.17)	*Moderate* benefit* (p<0.01, *d*=0.67)

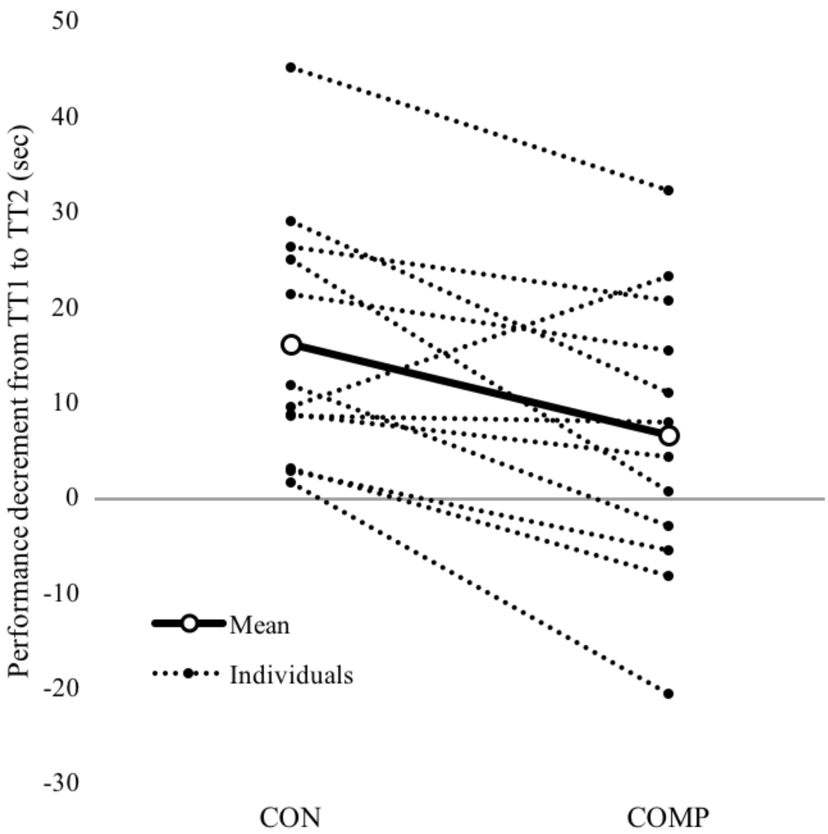

Figure 7.2 Individual performance decrements (s) from TT1 to TT2 for both CON and COMP.

Oxygen consumption and blood lactate significantly increased over the course of the exercise protocol (p<0.001 for both), but there was no main effect of condition (p=0.61 and p=0.54, respectively) or the interaction of time point*condition (p=0.34 and p=1.00, respectively, Table 2) for either variable. Oxygen consumption increased significantly, with each increment of the warm up protocol (*d*=2.30, p<0.01 from stage 1 to 2 and *d*=2.46, p<0.01 from stage 2 to 3). Blood lactate did not differ from the first to the second stage of the warm-up (*d*=0.33, p=1.00), but increased significantly for the third stage (*d*=0.81, p<0.01). TT efforts resulted in significantly higher blood lactate measures than the warm-up stages (*d*=2.80, p<0.01), but did not differ from TT1 to TT2 (*d*<0.01, p=0.10).

Table 7.2 Summary of physiological measures for (CON) and compression (COMP) conditions (presented as mean ± SD).

	Time point	CON	COMP	Difference between conditions
VO_2 (ml.kg^{-1}.min^{-1})	Warm-up (stage 1)	35.8 ± 1.9	37.1 ± 1.4	No difference (p=0.61)
	(stage 2)	41.6 ± 1.2	40.8 ± 1.2	
	(stage 3)	47.4 ± 1.9	47.7 ± 2.0	
BLa (mmol.L^{-1})	Warm-up (stage 1)	1.3 ± 0.2	1.7 ± 0.5	No difference (p=0.54)
	(stage 2)	1.3 ± 0.2	1.6 ± 0.4	
	(stage 3)	1.9 ± 0.3	2.1 ± 0.4	
	Post-TT1	9.2 ± 1.7	9.3 ± 2.2	
	Post-TT2	7.5 ± 1.4	7.8 ± 2.6	
Cross Sectional Area (cm^2)	Pre-Warm-up 1	115.8 ± 6.7	116.1 ± 6.7	No difference (p=0.63)
	Post-TT1	116.7 ± 7.0	116.2 ± 6.8	
	△CSA	0.9 ± 1.0	0.1 ± 0.8	

A main effect was apparent for time on perceived exertion ($p<0.01$). Runners' perceived exertion increased significantly as the warm-up progressed (*d*=0.90, $p<0.01$), and both TT efforts corresponded with significantly higher exertion than any stage of the warm-up (*d*=3.19, $p<0.01$). However, there was no difference between conditions at each of these time points.

Runners perceived their muscle soreness and fatigue to be similar regardless of intervention (p=0.56 & 1.00, respectively). Both parameters did however change over time, with significant increases in soreness and fatigue from pre-TT to post-TT on both occasions (*d*=1.05, $p<0.01$and *d*=1.75, $p<0.01$, respectively). During the recovery period, perceived soreness remained constant (p=0.14), while fatigue was reduced over the 60-minute period ($p<0.01$). Perceptions of recovery were also unaltered by the use of compression socks, with TQRPer similar between conditions (p=0.61). However, runner ratings did improve over the course of the recovery period (*d*=0.87, p=0.01).

Table 7.3 Summary of perceptual measures for (CON) and compression (COMP) conditions.

	Time point	CON	COMP	Difference between conditions
RPE (6-20 scale)	Warm-up (stage 1)	8.2 ± 0.9	8.2 ± 1.0	No difference (p=0.56)
	" " (stage 2)	9.7 ± 1.1	10.0 ± 1.1	
	" " (stage 3)	11.1 ± 1.3	11.2 ± 1.4	
	Post-TT1	18.0 ± 1.3	18.2 ± 1.2	
	Post-TT2	18.7 ± 0.8	18.7 ± 0.7	
Muscle Soreness (1-10 scale)	Pre-Warm-up 1	1.0 ± 0.6	0.8 ± 0.5	No difference (p=0.56)
	Pre-TT1	1.6 ± 0.9	1.6 ± 0.6	
	Post-TT1	3.7 ± 1.2	4.2 ± 1.1	
	Pre-Warm-up 2	4.0 ± 1.3	3.2 ± 0.7	
	Pre-TT2	4.6 ± 1.1	3.7 ± 0.8	
	Post-TT2	5.7 ± 1.2	6.0 ± 1.3	
Fatigue (1-10 scale)	Pre-Warm-up 1	1.1 ± 0.7	0.8 ± 0.5	No difference (p=1.00)
	Pre-TT1	2.0 ± 0.7	1.8 ± 0.7	
	Post-TT1	5.4 ± 1.5	5.6 ± 1.3	
	Pre-Warm-up 2	3.6 ± 1.1	3.3 ± 0.7	
	Pre-TT2	4.3 ± 0.9	4.5 ± 0.9	
	Post-TT2	7.1 ± 1.4	7.4 ± 1.1	
TQRP (6-20 scale)	Post-TT1 1	10.6 ± 0.2	11.4 ± 0.2	No difference (p=0.61)
	Pre-Warm-up 2	13.9 ± 0.2	13.8 ± 0.2	
	△TQRP	3.3 ± 2.4	2.4 ± 1.9	

Compression socks did not influence changes in calf cross-sectional area. There were no differences between conditions and no change in cross-sectional area from prior to warm-up 1 to immediately post-TT1 (d=0.01, p=0.64 and d=0.05, p=0.22, respectively).

Discussion

The primary finding from this investigation was that wearing compression socks during exercise can positively influence performance in a subsequent exercise bout (9.5sec in this population). This is a novel outcome, adding a further layer to research into sports compression garments, where the majority of previous investigations have studied the immediate effects of wearing compression garments during performance, or their efficacy when worn post-exercise[1,3,5].

The current study attempted to better understand any changes in running performance by assessing a multitude of mechanistic parameters that have previously been attributed to potential performance enhancements elicited by sports compression garments. Similar to the majority of previous investigations[21,68,77], blood lactate was not affected by the use of compression garments while running. Scientists have proposed that compression garments may enhance circulatory flow, and therefore hasten lactate removal[13], but this phenomenon is yet to be clearly displayed in an athletic setting. Oxygen consumption did not differ between experimental conditions either. This result is consistent with the findings of Rider and colleagues[77] and Stickford and colleagues[46], who both assessed the efficacy of compression garments while running on a treadmill. Similarly, assessments of calf CSA were no different between conditions in the present study, again reflecting previous research that has found no effect of compression garments on lower limb volume 5 minutes after the completion of 10km and marathon running efforts[68,140].

Although the aforementioned parameters could not justify the performance changes in this study, other mechanisms may have affected running performance. Reducing the workload required from the athlete in the first exercise bout would have improved recovery and allowed superior performance in the subsequent TT. A reduction in workload may have been brought about by improved oxygen delivery[15,141], reduced muscle oscillation[71], and a decrease in cardiovascular demands due to enhanced circulatory flow[13,73]. Hooper and colleagues[66] also suggested that compression garments increase proprioception, which may improve stride mechanics, therefore aiding biomechanical running economy and reducing potential muscle damage[142]. However, it must be recognised that this combination of outcomes is highly speculative, and focus must also be placed on the role that psychological factors, including a placebo effect, may play on athletic performance.

Surprisingly, the current study revealed no differences in perceptual measures between experimental conditions, unlike most previous research into the efficacy of compression garments. Several studies have reported athletes who wore compression garments during exercise to have experienced reductions in muscle soreness from 24-72h post-activity[24,68]. This disparity is likely due to the limited duration of the recovery period in the present study, which could have been too brief to realise any potential benefits of wearing compression socks while running.

Conclusion

In summary, wearing compression socks during high intensity running does not affect immediate performance. However, they have a positive impact on subsequent running performance. The underlying mechanism of such performance enhancement remains unclear, but may relate to improved oxygen delivery, reduced muscle oscillation and superior running mechanics.

Practical Implications

- Wearing compression socks while running does not affect immediate performance.
- However, compression socks worn during exercise can augment subsequent exercise bouts, so should be considered when athletic performances are scheduled in short succession.
- Compression socks worn when running also have the capacity to augment post-exercise recovery.

Chapter 8:

Thesis summary

Discussion and major findings

The purpose of this body of research was to assemble a more complete and comprehensive understanding of how sports compression garments can influence athletic performance and recovery. A multi-faceted approach was employed and the key findings of this thesis are that sports compression garments exhibit similar characteristics to medical grade garments, limb volume may be reduced when wearing compression, and recovery and subsequent exercise performance is augmented when sports compression socks are worn either during or after an initial exercise bout.

The first three studies aimed to bridge a gap in the literature by accurately quantifying the physical properties of sports compression garments, and precisely measuring the pressure they exert. Several authors have recognised that the equivocal results previously reported in the literature may be linked to the heterogeneity of garments investigated[1,16,27]. This thesis was able to use a valid, reliable tool to quantify that sports compression socks exert only marginally less pressure than medical grade compression socks and are therefore unlikely to induce any difference in physiological mechanisms. This finding allowed investigators to be confident that sports compression garments used in further studies would exhibit physical properties similar to garments that had previously been shown to elicit physiological alterations.

Previously it was believed that compression garments produced a graduated pressure profile. In determining a comprehensive pressure profile of sports compression tights and leggings our findings refute this premise. Different sports compression garments present dissimilar pressure application, that is neither graduated nor reverse graduated in nature. The lack of a distinct gradient illustrated across the assessed sports compression garments suggests that such a gradient may not necessarily be vital to eliciting a physiological response, with pressure applied to major muscle bellies likely to have a more significant impact.

To ensure a meaningful comparison of literature and an improved understanding of factors influencing the ergogenic potential of compression garments, this series of investigations has provided benchmark requirements for future compression studies. These include the application of a valid and reliable device to measure and report applied pressure, adopting a standardised posture for pressure measurements that are conducted at recognised landmarks, and ensuring the identification of garment type and sizing (Figure 8.1).

Athletic populations have rarely been recruited to assess the physiological mechanisms proposed to underlie the capacity for compression garments to aid performance and recovery. Most research in a sporting setting has measured surrogate measures such as heart rate and blood lactate, with extrapolations made to comprehend underlying physiological changes[21,25,63]. This thesis aimed to target this gap in the literature and investigate changes in arterial blood flow and whole limb volume when sports compression garments were worn by healthy participants, with a wide range of additional cardiovascular parameters also included to improve our understanding of any alterations in physiological mechanisms. Compression socks were found to reduce limb volume following orthostatic stress, suggesting that they have the capacity to aid in exercise recovery. Our study also produced some unexpected results, but these were able to be explained by the array of parameters assessed during the investigation. One such example being the lack of difference in blood flow and limb volume measures between sports compression garments and a control (no compression) possibly being rationalised by an increased respiratory rate compensating for the additional orthostatic stress in the control trial. This finding may help explain the lack of change shown between control and intervention conditions in previous studies, where only select parameters have been measured. The penchant for compression to reduce limb volume following exposure to orthostatic stress, and to possibly reduce load on the respiratory system illustrated the potential to impact exercise recovery, led to the assessment of compression socks in a practical, performance-centred setting.

Following a comprehensive investigation into the physiological mechanisms they elicit; compression socks were then found to aid subsequent performance when worn post-exercise. This conclusion is consistent with previous studies to report similar performance benefits[14,24,51-53]. However, contrary to much of the literature, a multi-faceted approach allowed for physiological, psychological and perceptual factors to also be taken into account. This uncovered the potential for athletes' beliefs to shape performance outcomes, with those who believed in the efficacy of compression garments to aid recovery performing better in the subsequent exercise test than those who were either undecided or did not believe that compression garments would assist them. This finding highlights the importance of considering pre-conceived participant beliefs in research areas where true placebo and blinded conditions are unattainable, such as sports compression garments, as they have the potential to heavily influence performance outcomes. Such beliefs should also be taken into account when considering whether sports compression garments can be beneficial in a practical setting.

The final investigation found no difference in initial exercise performance when compression socks were worn during a five kilometre time trial, much like previous studies to have tested the efficacy of compression garments during exercise[21,67,68,70]. However, depth was added to the investigation through the assessment of multiple parameters, as well as the inclusion of a subsequent exercise bout. This particularly novel aspect of the study showed wearing compression garments during exercise aided subsequent performance. Most of the literature has reported the effect of compression garments when worn during exercise, or the impact they have on recovery parameters post-exercise[1-3,17], but we are unaware of any investigations to have studied subsequent performance in the detail similar to this thesis. The study's findings will help shape practice in the field, with recognition of the capacity to augment subsequent performance promoting the idea of wearing garments during exercise, particularly when there is only a short recovery period available for athletes before their next performance.

Thesis Limitations

Study population size and gender

The majority of participants in the investigations included in this thesis were male athletes, particularly the latter three studies. We must therefore speculate on the ability to transfer our findings to female athletic populations. Further to this, a greater number of participants assessed would have allowed for greater statistical power and likelihood for results to be replicated.

Statistical analysis of performance changes

The published manuscripts from chapters six and seven reported the effect size of the change witnessed between intervention trials, but not the confidence intervals of these effect sizes. This detail illustrates that sports compression socks worn between repeated running time trials have a *moderate* effect on subsequent performance (d ±95%CI=0.62 ±0.80). Similarly, sports compression socks worn while running have a *moderate* effect on subsequent performance (d ±95%CI=0.67 ±0.80). Although not reported in the original manuscripts, this additional analysis does not affect the eventual outcomes reported.

Future research direction

Our findings support the use of sports compression garments to aid both recovery and subsequent performance, with their capacity to reduce limb volume and muscle soreness, as well as athletes' belief in their efficacy, all contributing factors to these outcomes. These results have helped shaped benchmark expectations for future research in the area, as well as prompting several interesting topics for further studies to investigate (Figure 8.1).

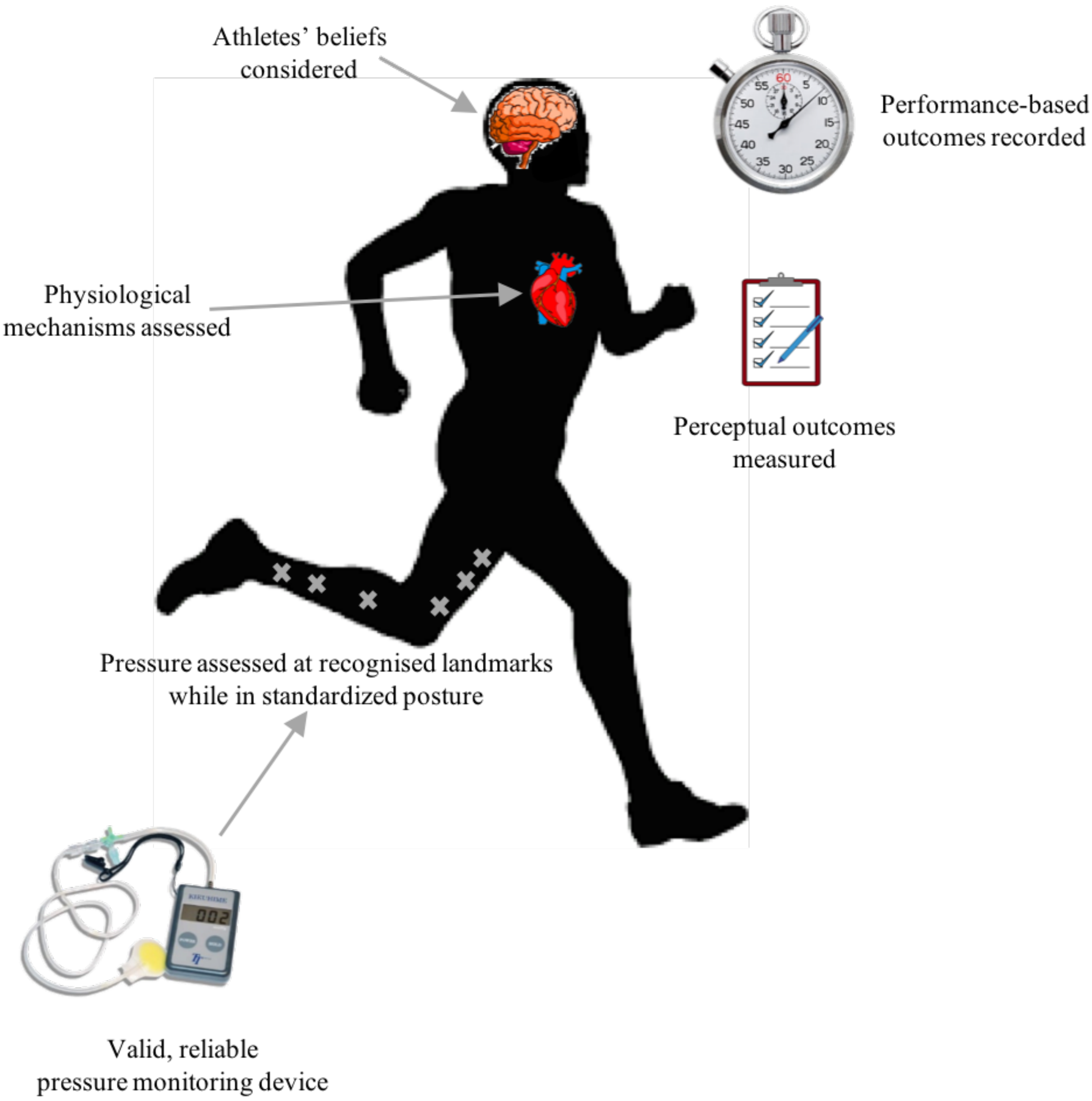

Figure 8.1 Schematic summarising important aspects to be included in future sports compression garment research.

The particularly novel finding of compression garments worn during exercise augmenting subsequent performance lends itself to further exploration into practical application in the field. Such an outcome suggests that compression garments would be particularly beneficial when used during sporting competitions that involve tournament-style play, with multiple rounds of competition scheduled over a short period of time. Future research should aim to broaden our understanding of this phenomenon, taking into account different sporting pursuits, as well as the capacity to augment performance beyond two consecutive exercise bouts.

The potential for athletes' beliefs to shape performance outcomes was another important conclusion from this thesis that will influence future research. The capacity for athlete expectations has previously been recognised in investigations assessing ergogenic aids[59,131], but not in research involving sports compression garments, where such measures are particularly pertinent, as a true placebo or blinded condition is not achievable. The manner in which a positive belief in the efficacy of sports compression garments to aid recovery was able to further enhance subsequent running performance highlights the importance of measuring psychological parameters. Such assessments should be incorporated in similar investigations so as not to miss a vital aspect of understanding how compression clothing might influence exercise performance.

The wide array of parameters assessed in this thesis has compiled a more complete understanding of how compression garments effect recovery and subsequent performance. Further depth could be added to the literature with the exploration of biomechanical parameters. Assessing whether sports compression garments can reduce muscle oscillation and improve proprioception while running, and more importantly, whether this can occur to a large enough extent so as to alter performance would provide novel outcomes that would continue to illustrate the primary mechanisms responsible for any performance changes.

Conclusions

Novel findings from this series of investigations has enabled an improved understanding of how sport compression garments can augment both recovery and subsequent performance, with clear connections displayed between changes in performance outcomes and the underlying mechanisms stimulating these alterations. These results display that compression garments can be considered an effective ergogenic aid to both recovery and subsequent performance when worn during or post-exercise. Recommendations are derived from the perceptual, physiological and performance-based outcomes investigated in this thesis and highlight the requirement for a multi-faceted approach in future research.

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Appendices

The use of compression garments in elite Australian athletes: a survey

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Running Title: Compression garments in elite athletes

Total word count: 1 763

Abstract word count: 313

Number of Tables: 3

Number of Figures: 2

This chapter has been published as:

Driller, M. W. & Brophy-Williams, N., The use of compression garments in elite Australian athletes: a survey, *Journal of Athletic Enhancement*, 2016.

Abstract

Objective: The use of compression garments is becoming increasingly popular amongst athletes as a method to enhance performance and/or recovery from exercise. However, little is known about the specific uses of compression garments and the perception of their benefit amongst elite athlete populations, therefore, the current study aimed to gain an understanding of the use of compression garments in the elite athlete setting.

Methods: The current study surveyed 236 elite Australian-representative athletes (160 male, 76 female) across a range of 16 sports (AFL, athletics, basketball, boxing, canoe slalom, football, gymnastics, netball, power-lifting, rowing, rugby union, rugby league, sailing, swimming, volleyball, wheelchair basketball) including Olympians (n=42) and Paralympians (n=28) from the 2012 London Games. The current use of compression garments, including which garments the athlete's own, how they are used, duration of wear and their perceived benefit was assessed. Further analysis was performed to assess the use of compression garments in athletes <20 years (n=116) versus athletes >20 years (n=120).

Results: The majority of athletes surveyed wear compression garments both during exercise and for post-exercise recovery 1-3 times per week. The most common duration for wearing compression garments was 1-4 hours following exercise (55% of athletes surveyed). The most common compression garments owned by athletes were long tights (89%), and 71% of athletes indicated that they sleep in their compression garments at least once per week. Mean ± SD for the benefit of compression tights for recovery (0= no benefit, 100 = definitely beneficial) was; 76.1 ± 17.4. There was a significantly greater perceived benefit of compression garments ($p < 0.05$) in athletes <20 years compared to athletes >20 years of age.

Conclusion: The majority of athletes surveyed perceived a benefit in wearing compression garments both during exercise and for recovery. The current study highlights the level of

perceived importance of compression garments as a performance and recovery tool in an elite athlete population.

Key words: Recovery, fatigue, performance, elite sport

Introduction

The use of compression garments and compression bandaging has been well documented in the medical literature as a method of treating circulatory disorders, predominantly through the prevention of venous stasis and the promotion of blood flow[1]. Given the efficacy of compression garments and bandaging as a treatment strategy in the medical setting, the use of compression garments in the athletic industry has become increasingly popular over the past decade. Several commercial companies in the sportswear business have made claims that the associated medical benefits can be applied to both exercise and recovery.

Compression garments are thought to improve venous return through application of graduated compression to the limbs from distal to proximal[2-4]. In an exercise-recovery setting, the promotion of venous return following exercise is thought to be an effective method in removing the metabolic waste products that accumulate during exercise, and therefore, enhance recovery[5,6]. In addition to improved blood flow, potential mechanisms that mediate performance gains when wearing compression garments appear to be related to a myriad of variables including enhanced proprioception[7], oxygen delivery and perfusion[4], improved heat tolerance[8,9] and the reduction in muscle oscillation during exercise[10]. The external pressure created by compression garments may also reduce the intramuscular space available for swelling, attenuating the inflammatory response and reducing muscle soreness[4-6,11]. Currently, the use of compression garments in the sports science literature seems to be more favourable towards its implementation as a recovery strategy rather than during exercise[1,12,13].

While the research into the effect of compression garments on both exercise and recovery is still somewhat limited, the exposure of compression garments is becoming increasingly prevalent, with many athletes, from amateurs to professionals, seen wearing the garments both during and following exercise. While we know that compression garments have been rated as a common recovery strategy following exercise[14,15], we are unsure of the exact way in which athletes are using the compression garments. Therefore, the aim of the current study was to examine the use and the perceived benefit of wearing compression garments in a range of elite athletes from different sports.

Methods

Subjects

The compression garment survey was completed by 236 Australian-representative athletes. All athletes volunteered to complete the survey and were competing at an elite level of competition in their respective sports when the survey was filled out. The survey was completed by 160 male and 76 female athletes which included athletes that competed at the 2012 Olympic (n = 42) and Paralympic Games (n = 28). Athletes were from a wide range of sports (AFL = 53; athletics = 13; basketball = 18; boxing = 3; canoe slalom = 11; football = 14; gymnastics = 8; netball = 22; power-lifting = 4; rowing = 6; rugby union = 16; rugby league = 3; sailing = 18; swimming = 22; volleyball = 11; wheelchair basketball = 13). A large majority of the athletes surveyed may have had existing personal sponsorship deals with different compression garment suppliers, however, athletes were informed that individual data would be confidential and reported anonymously without any effect on sponsorship agreements, and therefore, honesty was encouraged. The study received approval from the Institution's Human Research Ethics committee.

Procedures

The questionnaire was designed to gather information on athletes' opinions on the effect of compression garments and the ways in which they use compression garments (see supplementary files). In addition to background information relating to age, gender, sport and level of competition, the questionnaire contained questions about the different types of compression (e.g. tights, long-sleeve tops) that the athletes use. The questionnaire contained Likert response format questions designed to measure athletes' views towards the frequency/duration of compression garment use (e.g. very rarely, sometimes, often and very often). The athletes indicated their belief of whether compression garments were beneficial to recovery on a 100mm visual analogue scale (0 = no benefit, 50 = unsure, 100 = definitely beneficial). Athletes were also asked whether or not they regularly wore compression garments while sleeping (i.e. at least once a week).

Statistical Analysis

Findings are presented as descriptive statistics reporting the percentage of athletes responding to each descriptor on the Likert scale questions, as well as the means ± SD for the visual analogue scale response. A Microsoft Excel spreadsheet was used to estimate the mean effects and 90% confidence intervals (90%CI) of the perceived benefit when comparing those under and over 20 years of age[16]. Magnitudes of the standardized effects were calculated using Cohen's *d* and interpreted using thresholds of 0.2, 0.6 and 1.2 for *small, moderate and large*, respectively[17]. A T-test was used to compare those <20 years of age with those >20 years of age using a Statistical Package for Social Science (V. 22.0, SPSS Inc., Chicago, IL), with statistical significance set at $p \leq 0.05$.

Results

The majority of athletes surveyed ranked that they use compression garments for both recovery and during exercise 1-3 times per week (Table 1). The most common garment that was used by athletes were compression tights (89% of surveyed athletes), with the least common being the arm sleeves (11% of surveyed athletes, Figure 1). Further analysis of compression garment use was performed showing the percentage of use amongst athletes by each sport surveyed (Table 2).

Table 1. The use of compression garments as both a recovery strategy and during exercise. The table shows both the absolute values (number of athletes) as well as the percentage of athletes for each descriptor.

Question:	Very Rarely (once a month or less)	Sometimes (a few times a month)	Often (1-3 times per week)	Very Often (3 + times per week)
If you use compression garments as a RECOVERY strategy, how often do you use them?	16	70	95	55
	7%	30%	40%	23%
If you use compression garments DURING exercise, how often do you use them?	32	59	65	59
	14%	25%	26%	25%

Note – swimming athletes (n = 22) excluded from the 'during exercise' question as none of them had ever worn compression clothing while swimming.

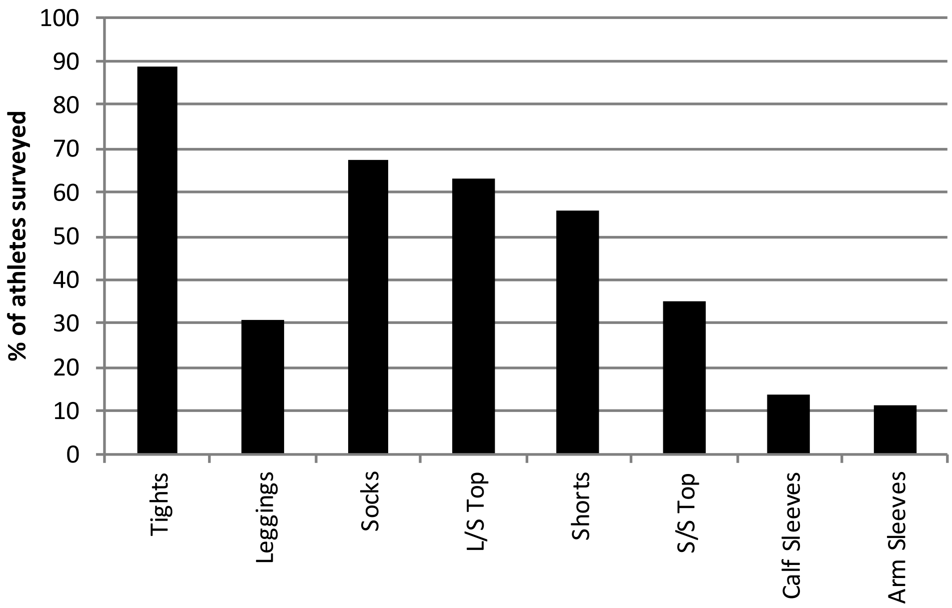

Figure 1. Different types of compression garments used by the surveyed group of athletes.

Table 2**.** Different types of compression garments used by each sport. Data presented as % of athletes from each sport that use specific garments.

Sport	Tights	Leggings	Socks	L/S Top	Shorts	S/S Top	Calf Sleeves	Arm Sleeves
AFL	91%	36%	85%	32%	92%	49%	30%	9%
Athletics	100%	15%	69%	62%	62%	15%	15%	8%
Basketball	100%	6%	72%	94%	94%	56%	6%	0%
Boxing	0%	33%	0%	33%	33%	0%	0%	0%
Canoe Slalom	91%	45%	73%	64%	36%	27%	18%	18%
Football	93%	29%	79%	93%	50%	21%	14%	14%
Gymnastics	88%	25%	100%	63%	38%	0%	25%	13%
Netball	100%	64%	80%	52%	84%	28%	4%	0%
Power-lifting	50%	0%	25%	100%	0%	25%	0%	0%
Rowing	100%	50%	67%	50%	17%	17%	0%	17%
Rugby Union	100%	31%	25%	56%	94%	81%	19%	19%
Rugby League	100%	33%	67%	100%	100%	67%	33%	33%
Sailing	94%	17%	78%	72%	6%	17%	6%	0%
Swimming	90%	15%	65%	85%	0%	15%	5%	35%
Volleyball	91%	36%	27%	55%	9%	18%	0%	9%
Wheelchair Basketball	3`%	31%	38%	100%	15%	54%	0%	23%

The majority of surveyed athletes (71%) reported that they slept in their compression garments at least once per week.

When asked about the belief the athletes had in compression garments aiding in recovery (0-100), the mean ± SD response was 76.6 ± 17.3 (Table 3). When athletes were group for age, there was a significantly greater belief in compression aiding recovery for those aged <20 years of age when compared those >20 years of age ($p < 0.05$, Table 3).

Table 3. The belief that compression garments aid in recovery from exercise (0=no benefit, 100=definitely beneficial) for the whole group surveyed and the comparison (p-value and effect size) for those under vs over 20 years of age.

Athletes	Mean ± SD	90% confidence limits	P-value	Effect Size (±90% confidence limits)
All (n=236)	76.6 ± 17.3	74.8 – 78.5		
<20 years (n=116)	79.2 ± 16.4	76.7 – 81.7	0.02	-0.32 ±0.22 *Small*
>20 years (n=120)	74.0 ± 17.9	71.3 – 76.7		

The majority of athletes (55%) reported that when they wear compression garments to aid recovery, they typically wear them for 1-4 hours following exercise (Figure 2).

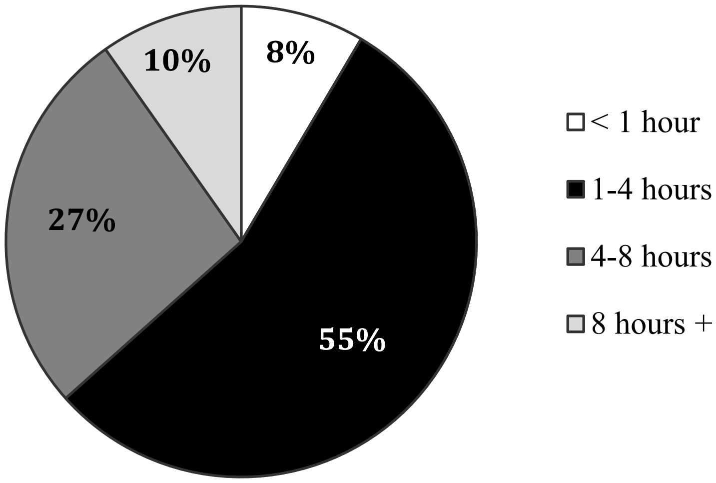

Figure 2. Time that athletes most commonly wear compression garments for following exercise (% of athletes surveyed).

Discussion

The current survey of 236 elite Australian athletes has highlighted the importance placed on using compression garments as a tool both during and following exercise. To our knowledge, this is the first study to describe the use and perceived benefit of compression garments in an elite athlete population. Results from the current study show that although the popularity of different garments varied between sports, overall compression tights were the most commonly owned by athletes, while the most common duration of wearing the tights were 1-4 hours following exercise. The majority of athletes also reported that they sleep in their compression garments at least once per week. An interesting finding was that when grouped by age (under and over 20 years), the younger athletes perceived the benefit of wearing compression to aid recovery as being significantly greater than those aged over 20 years.

While numerous studies have described the use of compression garments either during exercise[6], or as a recovery strategy[18,19], very little information exists regarding the actual use of compression garments in an elite athlete setting. Indeed, some previous research investigating the use of different recovery modalities following exercise fails to include compression garments as a recovery modality in their questionnaire[20,21]. However, the use of compression garments amongst professional athletes is becoming increasingly evident. Van Wyk and Lambert[15], investigated the use of recovery modalities prescribed by 58 support staff of elite rugby players in South Africa[15]. Their survey found that compression garments were the seventh most popular recovery strategy after a rugby game; ranked after stretching, cold water immersion, active recovery, massage, additional hydration and nutrition: extra carbohydrates. Additionally, the majority of support staff surveyed suggested that the most common reason for prescribing the use of compression garments was player injury. Bahnert et al.[14] investigated the use of recovery modalities in 44 Australian Football League (AFL) players throughout a season. Their survey found that the use of compression garments following AFL games was one of the top five recovery strategies, with 72.1% of athletes opting to use compression garments, with stretching again reported as the most common strategy.

While the current study is the first to assess the specific use of compression garments amongst athletes, numerous reviews and meta-analyses have described the significant perceived benefit to delayed onset of muscle soreness (DOMS), and overall recovery when using compression garments[1,12,13]. These findings are consistent with the survey in the current study, with the majority of athletes reporting a perceived benefit when wearing compression for recovery (Table 2). Similar to the results from studies outlined in recent reviews[1], athletes in the current study responded more in favour of wearing compression as a recovery strategy compared to during exercise (Table 1). There has been little research into the optimal duration for wearing compression garments, and this area requires attention in the future. Athletes in the current study reported that the most common duration for wearing compression following exercise was

1-4 hours. However, a large majority of athletes (71%) also reported that they sleep in their compression garments at least once a week.

Future research investigating the use of compression garments amongst an elite athlete population should focus on the reasons for their perceived benefit (e.g. own experience, marketing, other athletes, coaches/staff, scientific articles). The assessment of their position within the athletes' hierarchy of recovery modalities would also provide insightful information into their perceived importance. Finally, the perceived benefit of compression garments for athletes from a range of levels, abilities and years of sporting experience would also provide a better understanding of whether or not elite athletes are similar in their beliefs as lower level athletes. Indeed, results from the current study suggest that older athletes may not have the same beliefs about the benefit of compression garments. It is unknown whether this is due to greater levels of experience using compression garments or alternatively, scepticism around recovery strategies in general. Unfortunately, we did not gain further information about why these differences in belief occur with age, however this does provide an insight that is worthy of future research, not only on compression garments, but any recovery strategy.

This was the first study to investigate the specific uses and beliefs of compression garments amongst a population of elite athletes. Given the rise in popularity of compression garments in the sport setting, it is not surprising that the overall responses to the benefit of wearing compression garments were generally positive. The study gives us insight into the most commonly used compression garments, the duration of wear, when they are being worn and the belief in their efficacy.

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Supplementary Material

<u>Compression Garment Questionnaire</u>

Name: ____________________ Sport: _________________ Age:________

What type of compression garments do you use (if any)?
(Circle as many as appropriate)

Tights (Full)	Leggings (Ankle-mid thigh)	Socks	L/S Top
Shorts	S/S Top	Calf sleeves	Arm sleeves

If you use compression garments as a RECOVERY strategy, how often do you use them?
(Circle one)

Very Rarely (once a month or less)	Sometimes (a few times a month)	Often (1-3 times per week)	Very Often (3 + times per week)

If you use compression garments DURING exercise, how often do you use them?
(Circle one)

Very Rarely (once a month or less)	Sometimes (a few times a month)	Often (1-3 times per week)	Very Often (3 + times per week)

Do you believe that wearing your compression garments will benefit your recovery?
(Use a vertical line to mark your rating on the lines below)

No Benefit — Unsure — Definitely Beneficial

How long would you typically wear your compression garments for FOLLOWING exercise?
(Circle one)

Less than 1 hour — 1-4 hours — 4-8 hours — 8 hours +

Do you ever sleep in your compression garments? (Circle one)

YES — NO

The reliability of a 5km run test on a motorized treadmill

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Running Title: Compression garments in elite athletes

Total word count: 2 594

Abstract word count: 148

Number of Tables: 2

Number of Figures: 2

This chapter has been published as:

Driller, M. W., Brophy-Williams, N. & Walker, A., The reliability of a 5km run test on a motorized treadmill, *Measurement in Physical Education and Exercise Science*, 2017; 21(3):121-6.

Abstract

The purpose of the present study was to determine the reliability of a 5km run test on a motorized treadmill. Over three consecutive weeks, 12 well-trained runners completed three 5km time trials on a treadmill following a standardised warm-up. Runners were partially-blinded to their running speed and distance covered. Total time to complete the run was recorded for analysis of reliability. The highest intra-class correlation coefficient between trials for 5kmTT time was 0.99 (90% confidence intervals; 0.96 - 1.00, *very high*), which occurred between trials 2 and 3. The lowest typical error of measurement (expressed as a CV% and as an absolute value; seconds) also occurred between trials 2 and 3, and was: 1.0% and 10.9 seconds, respectively. The testing protocol performed on a motorized treadmill in the current study is reproducible in well-trained runners following a single trial, making it a reliable method for monitoring running performance.

Keywords: reproducibility, exercise test, athletic performance, running, test-retest

Introduction

Running performance in the laboratory has been closely related to running performance in the field in well-trained runners[1]. When monitoring exercise performance in the laboratory, accurately assessing ongoing training effects in athletes is critical to monitoring load and progression. As such, knowledge of test-retest reliability of laboratory based protocols, as a possible surrogate for field-testing, provides valuable information to determine whether changes in performance can be accurately detected with that protocol. Furthermore, understanding the test-retest reliability of given protocols may also help in the calculation of sample size and determine the precision required when monitoring performance changes in athletes. This is of particular importance when working with elite runners where improvements in performance are small, but may still be considered worthwhile in a competitive sport setting[2].

Unlike field tests in less controlled environments, treadmill testing in laboratories can provide standardized conditions, allowing assumptions made about performance variability to be based on changing training status, rather than test variability. When treadmill testing has been used to measure aerobic capacity through time to exhaustion (TTE) testing protocols, high levels of repeatability have been observed in well-trained runners[3]. However, this is in contrast to previous studies that demonstrated variability of up to 17% in participants who were not aerobically trained[4,5] and also up to 26.6% in cyclists[6]. Despite differences in repeatability, possibly the greatest limitation of TTE testing is that it may have low ecological validity, as it does not mimic real-world race conditions and athletes are asked to work at a pre-determined set intensity, thereby limiting their ability to pace their effort based on “feel” as they would in a race.

Time trial tests (TT) are generally considered to be more reliable than TTE tests, with <5% CV observed in a number of studies[5]. While the reliability of TTE testing has been previously assessed and validated[3], to our knowledge, TT testing on a treadmill has been limited to time-based, rather than distance-based trials. Specifically, in their research, Schabort et al.[7] had runners complete a 60-minute TT on a treadmill, where they could control their speed and also see the elapsed time, though not distance. The authors reported a CV of 2.7% which, they determined as being acceptable, although not suitably reliable to detect meaningful changes in elite athletes. The 5km running time trial (5kmTT) test performed on a treadmill is currently used in a number of sporting settings and University laboratories to assess and monitor running performance[8]. However, despite its widespread use in these settings, the 5kmTT treadmill run test is yet to be evaluated for its ability to accurately determine performance changes in runners[9-12].

In contrast to a 5kmTT on a treadmill, previous 5km run performance testing reported in the literature has been performed outside on a track[13] or on a non-motorized treadmill[14]. Despite Hurst and Board[13] reporting a mean CV of 0.95 ± 0.65% in an outdoor 5kmTT, the likely presence of wind, rain and variations in temperature and surface in other settings, may affect the reliability of this test compared with a more controlled laboratory environment. To our knowledge, the performance of a 5kmTT on a motorized treadmill, in a laboratory, where participants can self-select and adjust their pacing, while being blinded to distance covered, is yet to be critically evaluated. Thus, the aim of the present study was to determine the test-retest reliability of a 5km TT running test on a motorized treadmill in well-trained, competitive runners.

Methods

Subjects

Twelve well-trained male runners (mean ± SD; 5km run time = 19:21 ± 1:26 min:sec, height = 181.4 ± 6.9 cm, body mass = 77.8 ± 6.5 kg, age = 30.5 ± 8.1 years) who reported personal best 5km run times of <20 minutes and had a training history of at least four training runs per week for the past three years were recruited for the current study. Participants provided informed consent prior to any testing based on ethics approval from the Institution's Research Ethics Committee.

Design

To examine the test-retest reliability of a 5kmTT on a custom-built, motorized treadmill (Australian Institute of Sport, Canberra, Australia), participants attended three separate testing sessions over a 14-day period, each separated by a minimum of 5 and maximum of 7 days. The trials consisted of a standardized warm-up followed by a 5kmTT. Training throughout the testing period was not monitored by the researchers, however, all participants were asked to keep total training volume and intensity the same each week during the study. Participants kept training the same in the 48 h before testing on all occasions. All testing was performed at the same time of day (± 1 h) to minimize diurnal variation and on the same treadmill in a controlled laboratory setting (20 ± 1°C). Participants were asked to refrain from strenuous exercise (<24 h) and caffeine (<12 h) and to arrive at the laboratory in a fully rested, hydrated state. In order to control any dietary variables, participants completed a 24 h food diary prior to their first trial and were instructed to replicate their diet as closely as possible before the subsequent trials.

Procedures

The warm-up for the 5kmTT consisted of three 4-minute stages of submaximal running at 60%, 70% and 80% of participant-reported 5km race pace on a treadmill (mean speeds of 9.6 ± 0.6, 11.1 ± 0.7 & 12.7 ± 0.8 km.h^{-1}, respectively). A passive rest period of 1-minute was taken between each warm-up stage, and there was a 3-minute period between the end of the warm-up and start of the 5kmTT, where subjects walked on the treadmill at 4km.h^{-1}. The 5kmTT began at a speed 1 km·h^{-1} slower than the most recent mean speed for completion of a 5km race, as reported by each participant. The 5km race pace reported by participants was to be from a recent club race that was run weekly on a certified and timed 5km circuit, completed within 2 months prior to testing. While this intensity may have been either too high or low based on the current training status of participants, it was replicated exactly the same on all three occasions.

During the 5kmTT, participants were blinded to their elapsed time and run speed and standardized scripted encouragement was given by the researcher every 500m. Participants were also partially blinded to distance covered, with 500m milestones announced up until the final 500m, whereupon they received updates for each 100m covered (Figure 1). Participants were to indicate to the researcher for the speed to increase or decrease at any stage of the test by saying 'faster' or 'slower'. Total time was recorded at the completion of the 5kmTT and used as the main performance outcome measure. Both the warm-up and 5kmTT were performed with the treadmill gradient set at 0%. All participants reported having prior experience with running on the treadmill in our laboratory prior to taking part in the study.

Blood lactate concentration was measured via a capillary fingertip sample and was analysed with a Lactate-Pro 2 analyser (Arkray, Shiga, Japan). Samples were collected 3-minutes after the completion of each 5kmTT. The test-retest reliability of the Lactate-Pro 2 has been reported elsewhere[15]. During all tests, heart rate was recorded continuously using a RS800 heart rate monitor (Polar Electro Oy, Kempele, Finland). The average heart rate (HRmean) and maximum heart rate (HRmax) was collected over the entire 5kmTT and used for analysis. On completion of each 5kmTT, a rate of perceived exertion was also collected from participants using the Borg's 6-20 RPE scale[16]. RPE was only collected on completion of the test, as the researchers did not want to distract the participants during their 5kmTT. Asking for a RPE during maximal exercise may cause participants to alter their pacing strategy and it is preferable to let athletes run to their own pace with minimal distractions.

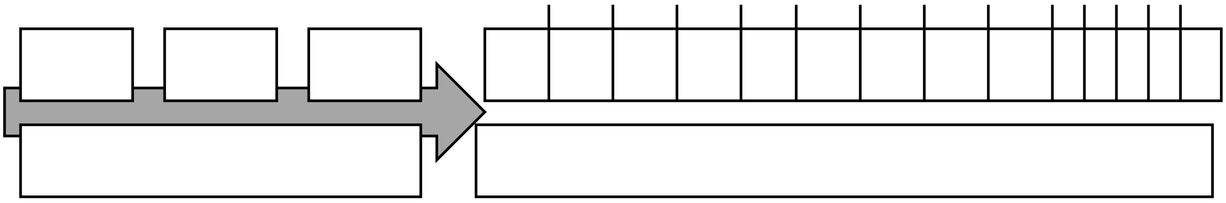

Figure 1. Schematic of testing protocol for the 5km TT. Individual marks during the work period represent verbal encouragement delivered at 500 m intervals and 100 m intervals over the final 500m.

Statistical Analyses

Descriptive statistics are shown as mean ± standard deviation unless stated otherwise. Test-retest typical error of measurement (TEM) was determined using a Microsoft Excel spreadsheet for reliability[17] and are presented as a coefficient of variation percentage (CV%) and as absolute values along with upper and lower 90% confidence intervals (90%CI). The intra-class correlation coefficient (ICC) between trials was also determined in combination with the 90%CI, and interpreted as 0.90–1.00 = *very high* correlation, 0.70–0.89 = *high* correlation, 0.50–0.69 = *moderate* correlation, 0.26–0.49 = *low* correlation and 0.00–0.25 = *little*, if any correlation[18]. A one-way repeated measures analysis of variance (ANOVA) with a Bonferroni correction was performed using SPSS v24.0 (IBM Corp, Armonk, NY, USA), with statistical significance set at $p<0.05$.

Results

There was no significant difference between trials in TT time ($p=0.053$), HRmax ($p=0.521$), HR mean ($p=0.378$), RPE ($p=0.375$) or lactate ($p=0.269$).

The fastest mean 5kmTT time was achieved during trial 2 (mean ± SD; 1161 ± 86 secs), with the average time across the three trials being 1176 ± 74 secs (Table 1). Average HRmax and blood lactate across the trials was 184 ± 7 bpm and 9.7 ± 3.1 $mmol \cdot L^{-1}$, respectively (Table 1).

Table 1. Mean performance and physiological variables for the 5km run test on a treadmill (5kmTT) over three separate testing sessions. Data are presented as mean ± SD.

	Test 1	Test 2	Test 3	Average
5kmTT (s)	1195 ± 53	1161 ± 86	1172 ± 80	1176 ± 74
BL ($mmol \cdot L^{-1}$)*	9.1± 2.4	10.2 ± 3.8	9.7 ± 2.8	9.7 ± 3.1
HRmax (bpm)	183 ± 7	183 ± 7	185 ± 7	184 ± 7
HRmean (bpm)	176 ± 7	175 ± 7	176 ± 8	175 ± 7
RPE	18 ± 2	18 ± 2	18 ± 2	18 ± 2

* Blood lactate taken 3-minute post 5kmTT.

The highest ICC and lowest TEM (expressed as absolute and CV%) for the 5kmTT were between tests 2 and 3 (Table 2). The CV% between trials 1 and 2 was 3.9% (absolute TEM of 35.1 s). The CV% between trials 2 and 3 was 1.0% (absolute TEM of 10.9 s).

Table 2. Mean intraclass correlation coefficient (ICC) and typical error of measurement (TEM) as a coefficient of variation (CV%) and as absolute values for each comparison (2 v 1, 3 v 2, 3 v 1). Comparisons include 5km run time (5kmTT), blood lactate (BL), maximum heart rate (HRmax) and mean heart rate (HRmean). Data are presented as means and 90% confidence intervals.

	5kmTT (s)	Lactate (mmol/L)	HRmax (bpm)	HRmean (bpm)
ICC$^{(2to1)}$	0.80 (0.50 - 0.93)	0.77 (0.44 – 0.92)	0.84 (0.61 – 0.94)	0.78 (0.48 – 0.91)
ICC$^{(3\ to\ 2)}$	0.99 (0.96 - 1.00)	0.79 (0.45 – 0.92)	0.77 (0.46 – 0.91)	0.71 (0.36 – 0.89)
ICC$^{(3\ to\ 1)}$	0.78 (0.56 - 0.91)	0.68 (0.43 – 0.85)	0.51 (0.30 – 0.73)	0.64 (0.41 – 0.83)
Mean ICC	0.89 (0.77 - 0.96)	0.78 (0.58 – 0.91)	0.76 (0.57 – 0.90)	0.75 (0.54 – 0.89)
CV$^{(2\ to\ 1)}$	3.2 (2.4 – 5.2)	19.9 (14.4 – 33.5)	1.7 (1.3 – 2.7)	2.0 (1.5 – 3.2)
CV$^{(3\ to\ 2)}$	1.0 (0.7 - 1.5)	19.0 (13.5 – 33.1)	2.0 (1.5 – 3.1)	2.4 (1.8 – 3.8)
CV$^{(3\ to\ 1)}$	2.8 (2.2 – 3.8)	15.9 (12.5 – 22.5)	2.3 (1.9 – 3.1)	2.2 (1.8 – 2.9)
Mean CV%	2.6 (2.2 – 3.2)	17.8 (14.7 – 23.7)	2.1 (1.8 – 2.7)	2.2 (1.9 – 2.8)
TEM$^{(2\ to\ 1)}$	35.1 (26.0 - 56.0)	1.7 (1.2 – 2.6)	3.1 (2.3 – 4.8)	3.5 (2.6 – 5.4)
TEM$^{(3\ to\ 2)}$	10.9 (8.0 - 17.3)	1.7 (1.2 – 2.8)	3.7 (2.8 – 5.7)	4.2 (3.1 – 6.5)
TEM$^{(3\ to\ 1)}$	30.7 (22.7 - 48.9)	1.3 (1.0 - 2.2)	4.3 (3.2 – 6.7)	3.9 (2.9 – 6.0)
Mean TEM	27.7 s (22.6 - 37.0)	1.6 mmol/L (1.3 - 2.1)	3.7 bpm (3.1 – 5.0)	3.9 bpm (3.2 – 5.1)

Blood lactate concentration had the lowest CV% and TEM between tests 1 and 3 (15.9% and 1.3 mmol/L, respectively). HRmean had the lowest CV% and TEM between tests 1 and 2 (2.0% and 3.5 bpm, respectively). Similarly, HRmax had the lowest CV% and TEM between tests 1 and 2 (1.7% and 3.1 bpm, respectively). The differences from the mean of all trials for 5kmTT time are shown in Figure 2. The figure supports the trend that there is a greater variation from the mean in the first trial, however, trials 2 and 3 show less variation, highlighting the increased reliability of the test following a single trial.

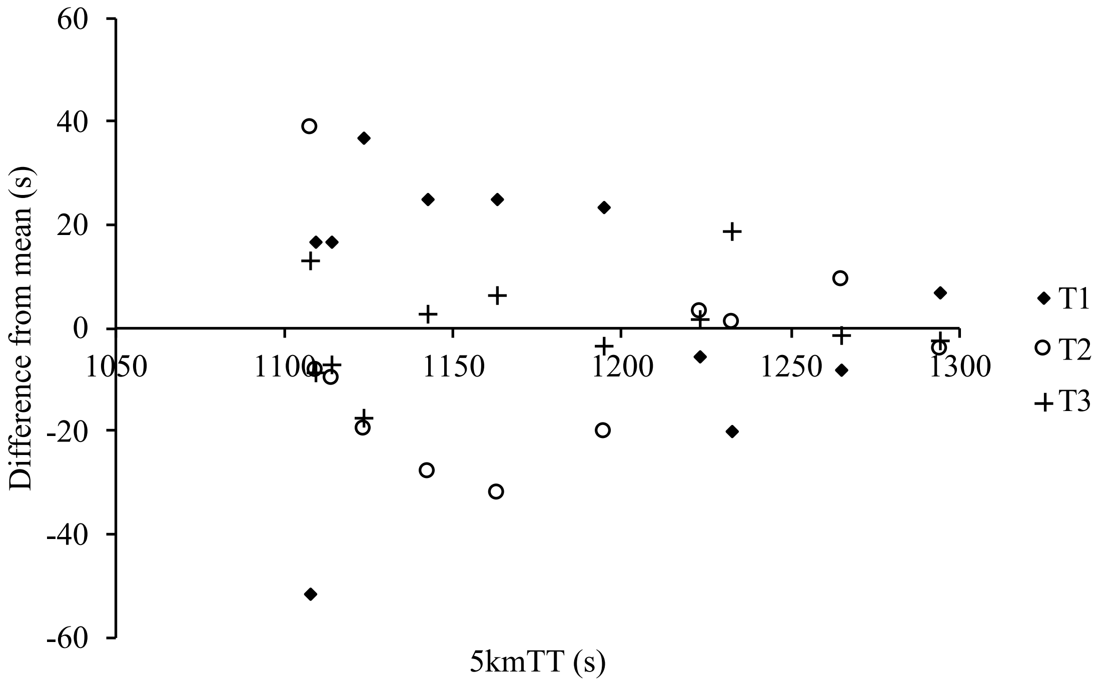

Figure 2. The mean difference (s) of each individual trial from the mean of three trials (T1, T2, T3) for the 5kmTT time (s).

Discussion

The primary findings from this investigation suggest that using a 5km running test on a motorized treadmill, results in highly reproducible performance in well-trained runners. The reliability of this test was associated with a low typical error of measurement (as expressed by CV%) and a *very high* intraclass correlation coefficient (1% and 0.99, respectively, Table 2). This typical error of measurement translates to just 10.9 seconds (90%CI: 8.0 – 17.3) during a 5km running test in a homogenous group of runners. The low TEM when using the current protocol suggests that this test can assist scientists and coaches to better understand factors that may influence running performance. Furthermore, the reliability of this test is greatly enhanced following the first trial. Therefore, scientists and researchers implementing this protocol may want to use a single familiarization session to ensure reliable results when using this test. This is illustrated by the improvement in reliability between tests 2 and 3, when compared to tests 1 and 2.

The purpose whereby athletes are blinded to their run time is important, as it does not allow athletes to simply aim to better their previous time and rather, they must run in reference to how they feel without external feedback. By using distance as the target outcome, it is likely a more valid measure of race performance[6] and therefore, may be an appropriate assessment of training adaptations. In a study using similar participants to the present study, Laursen et al.[1], found that a 5km time trial on a treadmill, run twice, resulted in a TEM of 2.0% (with a range of between 1.3-4.0%). The TEM is slightly higher versus those in our study for trial 3 compared with trial 2. This demonstrates a likely learning effect following the first trial, meaning that the protocol used in the current study appears to be appropriate for use as an ongoing performance assessment tool with athletes. Likewise, for non-athletic populations, consideration should be given to familiarizing participants prior to them completing a 5km TT in any laboratory-based studies. The value of familiarization trials has previously been observed and recommended, with the CV between trials reducing for subsequent trials[19].

Factors that may contribute to higher variability in performance versus those in the current study include the type of equipment and type of test used. Tests using an "open end" point (e.g. TTE tests) tend not to be as reproducible[20] with variability up to 15% previously observed between trials[1]. In tests with an undefined end point, psychological factors (such as motivation and boredom) may be more likely to influence performance. This has previously been considered when comparing lab based results against those recorded in competitive performances[19]. In tests that have a known end point, such as the test used in the current study, this is not as likely to have the same effect.

The authors would like to acknowledge some of the potential limitations in the current study. Unfortunately, hydration status was not assessed. The researchers asked participants to arrive in a hydrated state. Similarly, participants were also asked to refrain from caffeine and arrive in a rested state. These were not measured variables, they were assumed by the researchers. We acknowledge this is a potential limitation and would suggest that measures of hydration status would strengthen the reliability of this test. Furthermore, the current study did not assess perceived recovery/fatigue levels of participants before starting each trial. While we acknowledge this as a potential limitation, we attempted to control for levels of fatigue by asking participants to keep total training volume and intensity the same each week during the repeated trials, with training kept the same in the 48 h before testing, and all trials taking place at the same time of day on all occasions.

This study is the first to suggest that by using a well-controlled, time-blinded, practical testing protocol which includes a 5km running test on a motorized treadmill, it is possible to detect small, but meaningful changes in performance in well-trained runners. Although performing a 5km run on the track may increase the ecological validity of the test, this test performed in the laboratory may provide an appropriate, controlled, and readily available alternative for use in athlete monitoring and research studies. Allowing athletes to self-pace their run on the treadmill, while avoiding variations in environmental conditions (rain, wind temperature) make this test appropriate for measuring changes in performance. Given the typically low error of measurement across trials 2 to 3, it appears that only a single familiarization trial is required for future studies utilizing this test protocol, when using well-trained runners. We would suggest that future researchers implementing this protocol as a performance measure, should consider the reliability of the test following a single familiarization trial (CV = 1%, TEM = 10.9 seconds), and use these values when determining the smallest worthwhile change in performance. The test itself may be appropriate for use when evaluating different nutrition, training and recovery interventions, or even as a performance-monitoring tool in well-trained runners.

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Poster – 6th Exercise & Sports Science Australia Conference: Research to Practice, 2014

Haemodynamic Changes Induced by Sports Compression Garments and Changes in Posture

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INTRODUCTION

- Sports compression garments are frequently used by many athletes under the auspice that they are able to increase blood flow, and subsequently enhance recovery from exercise.
- Although compression garments have been show to improve blood flow in a clinical setting[1,2], these benefits have been extrapolated to underlie their use in a sports setting without extensive research having investigated their effects on athletic populations.

AIM

- To assess the changes in limb volume during and following an upright tilt test while wearing different sports compression garments (legging, sock and control).

METHODS

Participants. Eighteen active males took part in the present study (age 25.6 ± 5.0 years, body mass 62.6 ± 13.0 kg, x̄ = 394 ± 158 min physical activity/week).

Overview. Participants lay on a manually-operated tilt table, with a bike seat-like configuration between their legs so as to support their weight without the need for a foot plate (Figure 1)

Participants had their left leg fitted with either
(i) sports compression legging (**LEG**)
(ii) sports compression sock (**SOCK**)
(iii)no compression garment (**CON**)
In a counterbalanced order (Figure 2).
The right leg was considered a control.

Figure 2. Sports compression sock (left) and sports compression legging (right) used for testing.

After lying supine for 5 minutes, arterial flow was assessed using venous occlusion plethysmography (VOP).

- Protocol involved the inflation of a cuff on the upper thigh to occlude venous flow for three 10 second periods. Strain gauges measured changes in calf volume during this time, and the increase in volume over two cardiac cycles was used to derive a measure of arterial flow.

Continuous strain gauge readings were then recorded while participants were:

SUPINE remained in a supine posture for 5 minutes
UPRIGHT then were tilted to a 60º upright position for 5 minutes
RECOVERY returned to a supine posture for 5 minutes
(x̄ tilting time = 16 sec)
(See Figure 3)

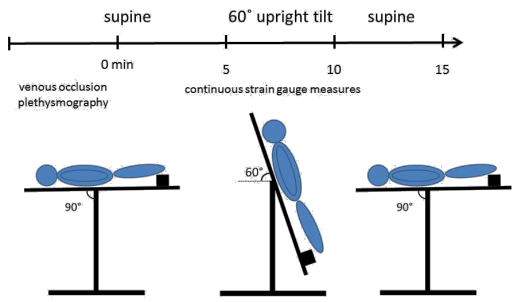

Figure 3. Experimental overview.

Additional measures taken included:
- heart rate (three-lead ECG)
- continuous blood pressure (Finapres® finger cuff)
- respiratory rate (respiratory strap)
- garment pressure (Kikuhime pressure monitoring device)

Haemodynamic responses were divided into **SUPINE, UPRIGHT** and **RECOVERY** phases, each of 5 minutes duration, for statistical analyses. Each condition was compared to control with a 2 way ANOVA (garment) x time (0-5min). Post-hoc (Bonferroni) analyses were used to assess any main effects that were apparent.

Figure 1. Upright phase of tilting protocol for **SOCK** condition

RESULTS

- No significant differences were apparent between garment conditions for resting leg blood flow (p>0.05), suggesting that neither sports compression socks nor sports compression leggings altered arterial blood flow to the calf.

- Garment pressure measurements

Garment pressure measurements	**SUPINE**	**LEG** > **SOCK** (p<0.02)
	UPRIGHT	no difference between garments (p>0.13)
	RECOVERY	**LEG** > **SOCK** (p<0.02)

SUPINE Limb volume did not differ between conditions (p>0.05) at the completion of five minutes of baseline assessment (**SUPINE**) (Figure 4).

UPRIGHT Following 5 minutes of **UPRIGHT** tilt, limb volume was significantly greater for **SOCK** compared to **CON** (p<0.001). No differences in limb volume were apparent between **CON** and **LEG** (p=0.71).

RECOVERY When participants were returned to a supine position (**RECOVERY**), **SOCK** resulted in the greatest decrease in limb volume, significantly more than both **LEG** and **CON** (p<0.001). Leg volume in **LEG** decreased significantly more than **CON** (p<0.001).

There was no significant difference between conditions for heart rate, blood pressure and respiratory rate in each posture.

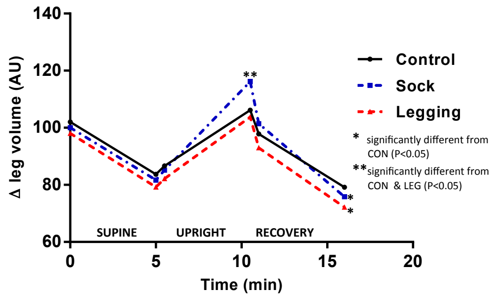

Figure 4. Change in limb volume from baseline (100AU) before, during and after tilt, with sports compression sock, legging and no garment (control) affixed to the left leg.

CONCLUSION

Sports compression garments appear to have a significant impact on the limb volume of an athletic population when the body is placed under orthostatic stress. These results reflect the hypothesised fluid shifts brought about by sports compression garments when used in a post-exercise recovery setting.

Further research is required to determine whether these fluid shifts are large enough to promote a sports performance or recovery benefit.

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The authors acknowledge 2XU (Melbourne, Australia) for supplying the compression garments used in this study. Please recognise that 2XU had no input on the study design, data collection or analysis, and has no right to approve or disapprove the publication of this research.

Physiological, Perceptual and Performance-based effects of compression socks – *Are they just a placebo?*

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INTRODUCTION

- Sports compression garments are often used post-exercise to hasten recovery.
- Studies thus far have provided equivocal results on their efficacy, with some literature suggesting that reported benefits can be largely attributed to a placebo effect (Duffield, 2010).
- The nature of compression socks makes it difficult to perform blinded trials, and, as such, exclude the possibility of a placebo effect (MacRae, 2011).

AIM

This study aimed to determine the effect of wearing knee-length compression socks between repeated running bouts on perceptual, physiological and performance-based parameters.

METHODS

Participants

Table 1. Participant characteristics

n	5km time	Age	Height	Weight
12 ♂	19:24 ± 1:21min	29.3 ± 9.0y	180.0 ± 6.0cm	76.1 ± 5.4kg

Protocol

After providing consent to participate in the study, runners were surveyed on their beliefs of the efficacy of compression socks for exercise recovery using a visual analogue scale.

Participants then completed a familiarisation session, followed by two experimental sessions. Each session involved the completion of two 5km time trials (TT1 and TT2), both run on a treadmill, with a one-hour recovery break between efforts (Figure 1).

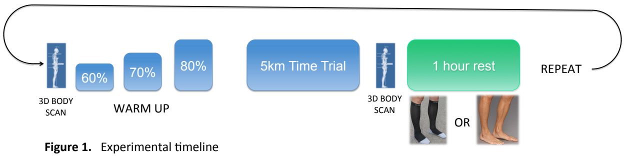

Figure 1. Experimental timeline

Sessions were completed under one of two conditions

- REC: where compression socks (mean pressure at calf = 22.7 ± 10.7mmHg) were worn during the one-hour recovery break
- CON: no compression garments were worn during the one-hour recovery break

Participants were assigned to the interventions in a randomised counter-balanced order.

Prior to each TT, warm-ups were run at 60, 70 and 80% of race pace, with each stage lasting four minutes. Oxygen consumption and heart rate were assessed throughout the warm-up, and blood lactate and ratings of perceived exertion were recorded at the end of each stage.

TT performance was considered to be the primary outcome measure with perceived muscle soreness and fatigue also recorded before and after each TT.

A 3D body scanner was used to assess changes in limb girth from before TT1 to after TT1, then again following the one-hour recovery period.

RESULTS

No significant differences were apparent between conditions for TT1 ($p>0.05$), allowing changes for TT1-TT2 to be compared without further transformation.

All Participants

REC – no significant decrement in performance from TT1 to TT2 ($p=0.20$)
CON – performance ***decreased*** significantly in TT2 ($p<0.01$)
The difference in performance decrement between REC & CON was moderate (10.6 ± 14.5s, mean ± 95% confidence limits, $p=0.07$, $d=0.62$).

No differences between conditions at submaximal running speeds for oxygen consumption, heart rate or perceived exertion ($p>0.05$). Similarly, the 3D body scans revealed no differences in calf girth between conditions.

Data was then split into two groups according to participants' belief in the efficacy of compression socks for exercise recovery.

Participants with Positive Perceptions (n=7)

Appeared to run slightly faster in TT2 than TT1 for the REC condition, and significantly slower in TT2 in the CON condition (Table 2).

Participants with Neutral or Negative Perceptions (n=5)

TT2 was substantially slower than TT1 for both REC and CON (Table 2).

Table 2. Change in performance from TT1 to TT2 according to athlete perceptions of the efficacy of compression sock for performance recovery

Group	Condition	TT1 (mm:ss)	TT2 (mm:ss)	Performance decrement	p value	Effect size
Combined	CON	19:24 ± 0:51	19:41 ± 0:53	15.9 ± 8.5s	**<0.01**	0.19 (small)
	REC	19:34 ± 0:48	19:40 ± 0:48	5.34 ± 13.2s	0.20	0.07 (trivial)
Positive perceptions	CON	19:24 ± 1:08	19:42 ± 1:05	17.9 ± 21.2	**0.02**	**0.23 (small)**
	REC	19:32 ± 1:09	19:28 ± 0:58	-3.6 ± 17.8	0.32	0.05 (trivial)
Negative/ neutral perceptions	CON	19:24 ± 2:03	19:38 ± 2:14	16.9 ± 14.6	**0.02**	**0.14 (small)**
	REC	19:37 ± 1:46	19:55 ± 2:00	17.9 ± 21.2	**0.04**	**0.19 (small)**

Perceptual Responses

At the end of the recovery period, muscle soreness ($p=0.03$) and fatigue ($p=0.04$) were significantly lower in REC than CON. Prior belief on compression socks had no effect on these ratings.

CONCLUSION

Compression socks worn during a recovery period between running bouts maintain subsequent performance and reduces self-reported muscle soreness and fatigue. Belief in the efficacy of compression socks may confer further performance benefits.

Further research is required to determine whether other physiological factors, not assessed in the present study, may also help elucidate changes in recovery and subsequent performance.

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